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SPECIAL ISSUE

An Overview of Toxic Contaminants in Water and Sediments of the Great Lakes

by:

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PREFACE

This is the second Monograph in the series published by the Canadian Association on Water Pollution Research and Control. It deals with toxic chemical pollution of the Great Lakes, one of the major contamination issues in Canada. The Monograph overviews the historical data on the concentrations of toxic metals and organic chemicals in the waters and sediments of all five of the Laurentian Great Lakes.

The literature search took place in mid-1988 and the first draft of the report was completed in January 1989. Subsequent reviews and editorial changes greatly reduced the original length. Many figures were combined or replaced by text and tables. Text was also replaced by more comprehensive tables. The final draft was completed in mid-1989. The indexed bibliography is a valuable extension to the report itself and of use to those who may wish to focus in greater detail on specific topics.

We are pleased to present this comprehensive synthesis of data relevant to one of the most pressing environmental issues of the past two decades to the Canadian water pollution research and control community and thank the authors for their contribution to the Monography Series of the Canadian Association on Water Pollution Research and Control.

J. Barica and D. Chapman, Editors
Water Pollution Research Journal of Canada

About the Authors

From 1980 to present, Dr. Rod Allan has directed the research of first the Environmental Contaminants Division (ECD) and then Lakes Research Branch (LRB) of the National Water Research Institute (NWRI), Environment Canada at the Canada Centre for Inland Waters (CCIW). The early research of these groups was directed towards toxic chemical pollution of the Niagara River and its impact on Lake Ontario, then on the St. Clair River and its input to Lake St. Clair, the Detroit River and Lake Erie and finally the St. Lawrence River and the fate of toxic chemicals in the St. Lawrence Estuary.

Dr. Allan is the author of over 100 scientific papers and reports including a 1987 review of the Role of Particulate Matter in the Fate of Contaminants in Aquatic Ecosystems. He has a First Class Honours B.Sc. from the University of Aberdeen in Scotland; a M.S. from the University of Wisconsin in Madison; and a Ph.D. from Dartmouth College in Hanover, New Hampshire, USA. He also holds an earned Doctor of Science degree (D.Sc.) from the University of Aberdeen.

Ms. Alison Ball is now a Librarian with Searle Canada Inc., an international pharmaceutical company. Her work on this report followed her graduation with an M.L.S. from the Faculty of Library and Information Science, at the University of Toronto, Ontario. Prior to her return to graduate school, Ms. Ball spent several years in the Yukon where amongst other activities she was involved with limnological studies of the Yukon River headwater lakes. Ms. Ball holds an Honours B.Sc. degree from Brock University.

WATER POLLUTION RESEARCH JOURNAL OF CANADA

This volume of the Water Pollution Research Journal of Canada is a Special Issue also being released by the Canadian Association on Water Pollution Research and Control as No. 2 in their Monograph Series. For further information on obtaining copies of this and other Monograph or Special Issues, please refer to the pages marked as such in the forward section of this issue.

A software version of the bibliography is also available. The bibliography was developed to be used in machine-readable form using the microcomputer-based PROCITE software (version 1.4). This software offers free-text and controlled vocabulary boolean searching.

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An Overview of Toxic Contaminants in Water and Sediments of the Great Lakes
Part I

R. J. Allan and A. J. Ball[1]

Introduction

The Great Lakes constitute the largest body of freshwater on earth. Ranked by surface area, Lake Superior is the second largest lake in the world. Lake Huron comes fifth, Michigan sixth, Erie thirteen, and Ontario seventeenth (Beeton 1984). The Great Lakes are viewed as one of the planets great natural resources, not only by the Canadians and Americans who live in their drainage basin (Figure 1) but by people around the world. In spite of the size of these waterbodies, man has contaminated them with toxic chemicals. The sources of the chemicals are urban and industrial development and agriculture. Some of the toxic chemicals are distributed throughout the entire Great Lakes ecosystem.

The purpose of this review is to present results of selected toxic chemical concentrations in the water and bottom sediments of the open Great Lakes and their connecting channels. Spatial patterns and temporal trends in these abiotic media are presented where possible.

The introductory section consists of background information about toxic chemicals in the water and sediments of the Great Lakes. This includes sources, pathways and fate of the chemicals in the system, a discussion of the main chemicals of concern, a history of Great Lakes contamination, and a description of water and sediment sampling and analysis. The overall organization of this report is by geographic location; that is, the data for each lake and connecting channel is presented in sequence from Lake Superior to the international section of the St. Lawrence River. For each body of water, the conditions of the water and then the sediments are discussed. The water sections are divided into two sections. The

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[1] Lakes Research Branch, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario, Canada.

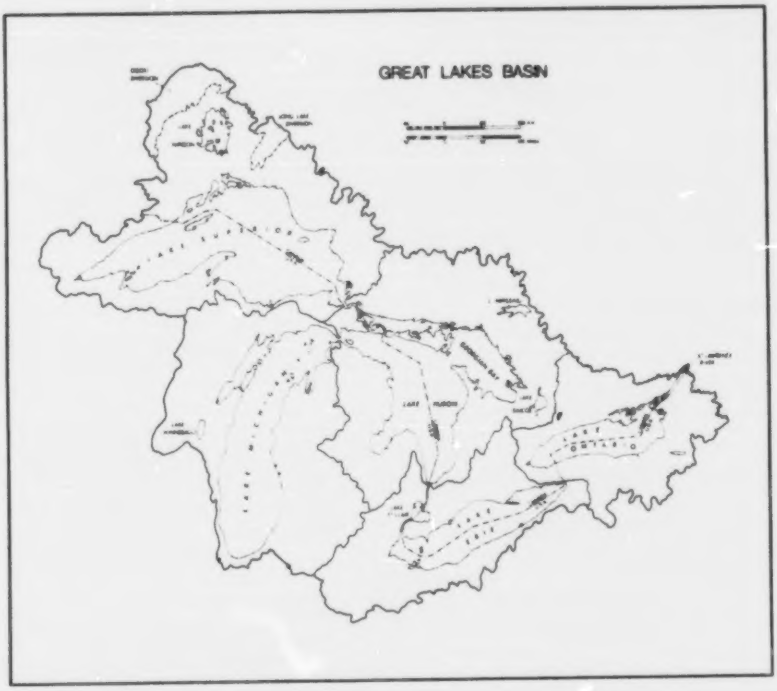

Figure 1. The Great Lakes drainage basin.

first section includes concentrations in the aqueous phase and in total water and the second section includes concentrations in the suspended sediment phase. The sediment sections are also divided into two parts: surficial sediment concentrations and concentrations in sediment cores. In each of these four sections, concentrations of metals are discussed before those of organic toxic contaminants. The main chemicals included for discussion in this report are lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), DDT and metabolites, dieldrin, α-BHC lindane, mirex, toxaphene, B(a)P, dioxins and furans, HCB, HCBD, and PCBs. There is a list of chemical abbreviations in Appendix 1. For each of the Great Lakes and the Niagara River, there are extensive tables of concentrations of these chemicals in the water and sediments. Representative core profiles for each of the Great Lakes show sediment concentration trends. The summaries for geographic patterns of contaminant distribution and concentration changes over time are presented in the conclusion. There is a glossary in Appendix 2.

Presently, the available information on toxic chemical contamination of the Great Lakes is greater than exists for any other set of freshwater lakes in the world (Allan 1988). This report is the most comprehensive document prepared to date on the concentrations of toxic contaminants in the water and sediments of all of the Great Lakes and their connecting channels. The sources used to prepare this literature review included journal articles, journal issues, reports, conference papers and proceedings, dissertations, monographs, and chapters. When possible, only primary published sources were used.

Toxic Chemical Sources, Pathways and Fate

The Great Lakes system flows from Lake Superior and Lake Michigan through the other Great Lakes and the St. Lawrence River to the Atlantic Ocean. The lakes are one unit in that they are connected by short narrows at Mackinac and by the short connecting channels of the St. Clair, Detroit and Niagara Rivers. These channels have extremely large discharges of approximately 6,000 m^3/sec, putting them on a scale with the world's largest rivers. The massive transfers of water into and out of lakes Erie and Ontario are a critical factor in toxic chemical fate in the lower Great Lakes. Less than 1% of the total volume of water in the system flows out annually by the St. Lawrence River. The residence times of the lower Great Lakes are dominated by the flows of the connecting channels (Table 1).

Major sources of many toxic chemicals to the lower Great Lakes are from industrial and municipal discharges to the connecting channels and other tributaries (NRTC 1984; UGLCCS 1989). Most chemical contamination control action has historically been directed and continues to be directed at these sources. Canadian industry is concentrated along the shore of the St. Clair River. Detroit and Windsor are located on the shores of the Detroit River. Buffalo is located immediately upstream of the Niagara River along which there has been major industrial development on the United States side. The channels rapidly transfer chemicals discharged along their course to the downstream lakes. For example, there is little or no long term removal of chemicals by burial in the bottom sediments of the Niagara River (Mudroch and Williams 1989). Another important result of the high discharges in the channels is that chemical inputs are quickly diluted to extremely low concentrations in the water phase. Alternatively, because of the high discharge, these extremely low concentrations can translate into large inputs to downstream lakes.

The two largest conurbations in the Great Lakes Basin are the Gary-Chicago-Milwaukee area of southwestern Lake Michigan and the Hamilton-Toronto area of northwestern Lake Ontario. Toxic

	Superior	Michigan	Huron	Erie	Ontario	Totals
Elevation (km)	183	176	176	173	74	
Length (km)	563	494	332	388	311	
Breadth (km	257	190	245	92	85	
Average Depth (m)	147	85	59	19	86	
Maximum Depth (m)	405	281	229	64	244	
Volume (km^3)	12,100	4,920	3,540	484	1,640	22,684
Area:						
Water (km^2)	82,100	57,800	59,600	25,700	18,960	244,160
Land Drainage Area (km)	127,700	118,000	134,100	78,000	64,030	521,830
Total (km^2)	209,800	175,800	193,700	103,700	82,990	765,900
Shoreline Length (km)	4,385	2,633	6,157	1,402	1.146	17,017
Retention Time (years)	191	99	22	2.6	6	
Population:						
U.S. (1980)	556,100	13,970,900	1,321,000	11,347,500	2,090,300	29,287,800
Canada (1981)	180,440		1,051,119	1,621,106	4,551,875	7,404,540
Totals	736,540	13,970,900	2,372,119	12,968,606	6,642,175	36,692,340
Outlet	St. Mary's River	Straits of Mackinac	St. Clair River	Niagara River Welland Canal	St. Lawrence River	

Table 1. Physical features of the Great Lakes (after Botts and Krushelnick 1987).

metals and organic chemicals are introduced to the lakes by urban runoff, via storm sewers and by many sewage treatment plants.

Today, non-point sources of chemical contamination, such as the atmosphere; agricultural runoff; and in-place, historically contaminated bottom sediments in bays, harbours, tributaries and in the lakes themselves, are recognized sources of contaminants to the lakes. Agricultural practices are sources of pesticides to tributaries to Lakes Michigan, Erie and Ontario, in particular. Because of their surface area, atmospheric deposition is a major source of chemicals to the Great Lakes (Strachan and Eisenreich 1988).

The Great Lakes are frequently referred to as inland seas yet the processes such as sedimentation, photodegradation and bioaccumulation which control the fate of chemicals in these large lakes are similar to those for smaller lakes. Toxic contaminants which are highly insoluble in water are found at interfaces between water and other aquatic compartments such as inorganic and organic solids in the water column or at surface microlayers between the water and the atmosphere. If associated with particulates, toxic chemicals become subject to limnological processes such as sedimentation and focusing in depositional basins and burial in bottom sediments. This latter process is a major process for aquatic ecosystem self-cleansing. In the deep lakes (Superior, Michigan, Huron and Ontario) toxic chemicals which have accumulated in bottom sediments are eventually buried beneath cleaner sediments and removed from bioaccumulation pathways. The depth and size of the lakes also affects their biological productivity and thus chemical fate. Nutrient loads to the lakes affect productivity. The relationship of nutrient status to toxic chemical fate is not well established but if a lake is nutrient rich, it is thought that this reduces toxic chemical concentrations at the top of aquatic food webs. The response of each lake to contamination by or control of toxic chemicals is thus somewhat unique. The fate of toxic chemicals in lakes is also governed by the physicochemical characteristics of the chemicals. These latter include solubility; volatility; hydrophobicity; lipophilicity; degree of partitioning onto suspended solids; and susceptibility to photo- and biodegradation. Once released to aquatic ecosystems, some chemicals rapidly disappear either by degradation or volatilization to the atmosphere. Degradation of chemicals to innocuous products can take place by a variety of chemical and biological processes including hydrolysis, photolysis, and bacterial or fungal dechlorination. Alternatively, even short lived chemicals can be highly toxic while they are in the water column.

Main Chemicals of Concern

It is the toxic metals and persistent toxic organic chemicals which have generated most concern about contamination of the Great Lakes. The latter includes chlorinated pesticides such as DDT and Mirex, chlorinated benzenes, chlorinated dioxins and furans, and PCBs. The former includes Pb, Hg, Cd, and As.

In 1983, a comprehensive Inventory of Chemical Substances Identified in the Great Lakes Ecosystem was published by the IJC. Produced from this inventory was the 1986 Working List of Chemicals in the Great Lakes Basin (IJC Comprehensive Track chemicals) which contains 362 chemicals (IJC 1987b). Of these chemicals, 11 critical pollutants were chosen by the IJC for their Primary Track. Information used in deriving priority lists tends to include chemical stability leading to persistence in the environment, the quantities in use, the types of use, the tendency to accumulate in living organisms, and the biological effects associated with acute or chronic exposure (Hamilton *et al.* 1987). In this report, all of the Primary Track chemicals are discussed plus several of the Comprehensive Track chemicals.

In Canada, there are several sets of objectives and guidelines set for concentrations of toxic chemicals in water. Two of these are presented in Table 2. When developing and using guidelines for the protection of aquatic life, there should be complete information on the chemical of concern, including form and fate in the aquatic environment; quantitative exposure/effect relationships; and fate within organisms over a wide range of exposure concentrations. The relevant information base for a particular chemical is rarely complete and there are often many gaps in knowledge. In general, water quality guidelines used in Canada are based on an unfiltered water sample (CCREM 1987).

The first set of objectives listed are the 1978 Great Lakes Water Quality Agreement Specific objectives. These were amended by the 1987 Protocol. Although the Protocol stated that the discharge of toxic substances in toxic amounts be prohibited and the discharge of any or all persistent toxic substances be virtually eliminated (IJC 1988), the Specific Objectives listed in the revised 1978 Agreement were adopted in 1987 as interim objectives for persistent toxic substances.

The second set of guidelines are those proposed by the Canadian Council for Resource and Environment Managers. In 1984, CCREM approved the recommendation by the Task Force on Water Quality Guidelines that Canadian water quality guidelines be harmonized (CCREM 1987). The guidelines are presented here as a comparison to the IJC objectives. The introduction to the Task Force report states that the guidelines should not be regarded as blanket values for national water quality and that variations in environmental conditions across Canada will affect water quality in different ways such that many of the guidelines will need to be modified according to local conditions (CCREM 1987).

Because the role of sediments as a source of chemical contaminants to the aquatic environment is poorly understood, criteria and standards are still being developed. The existing criteria for open lake disposal of dredged materials were developed as a guide to determining appropriate disposal techniques for dredged materials, not for ambient water quality evaluation and/or ecosystem risk assessment. The guidelines are as follows: Hg, 0.3 ppm; Pb, 50 ppm; Cd, 1.5 ppm; As, 8 ppm; and PCBs, 0.05 ppm. For other organic contaminants, the guideline is below detection using best available technology.

	1978 Great Lakes Water Quality Agreement Specific Objectives[1] ppb(μg/L)	CCREM water quality Guidelines for Aquatic Life[2] ppb(μg/L)
Pb	2.0-5.0[4]	1.0-7.0
Hg	0.2	0.1
Cd	0.2	0.2-1.8
As	50.0	50.0
DDT	0.003	0.001
Aldrin/Dieldrin	0.001	
Dieldrin		0.004
BHC	DL[5]	0.01
Lindane	0.01	
Toxaphene	0.008	0.008
PCBs[3]	0.001	0.001
HCB	DL	0.0065
HCBD	DL	0.1
2,3,7,8-TCDD	0.00001	
B(a)P	0.01	
Mirex	0.005[6]	

[1] IJC 1987c. These Specific Objectives are from the 1978 Great Lakes Water Quality Agreement or those subsequently approved by the IJC. Unfiltered water sample.

[2] Canadian Council of Resource and Environmental Ministers 1987. Unfiltered water sample.

[3] Total PCB, proposed objective.

[4] Concentration depends on lake (the lower lakes have higher objectives than the upper lakes)

[5] Detection Limit. "For other organic contaminants, for which Specific Objectives have not been defined, but which can be demonstrated to be persistent and are likely to be toxic, the concentrations of such compounds in water or aquatic organisms should be substantially absent, i.e., less than detection levels as determined by the best scientific methodology available" (IJC 1978).

[6] "For the protection of aquatic organisms and fish-consuming birds and animals, mirex and its degradation products should be substantially absent from water and aquatic organisms. Substantially absent means less than detection levels as determined by the best scientific mehtodology available" (IJC 1978). The level of 0.005 ppb is a change in the level approved by the Commission (IJC 1987c).

Table 2. Water Quality Agreement objectives for the main chemicals discussed.

	Dry Weight	Wet Weight
ppm parts per million	mg/kg milligram per kilogram	mg/L milligram per litre
ppb parts per billion	μg/kg microgram per kilogram	μg/L microgram per litre
ppt parts per trillion	ng/kg nanogram per kilogram	ng/L nanogram per litre
ppq parts per quadrillion	pg/kg picogram per kilogram	pg/L picogram per litre

Table 3. Units of measurement.

In this report concentrations are reported in ppm, ppb, ppt or ppq. Examples of the wet and dry weight concentrations these represent are given in Table 3.

History of Contamination

The recent history of toxic chemical pollution events began in the early 1960s with pesticides such as DDT, followed by detection of other organochlorine pesticides and industrial chemicals such as PCBs (Williams 1975; D'Itri 1988). In 1968, Hg was detected in high concentrations in sediments from lakes Ontario and Huron (Thomas 1972; 1973). Concurrently, high concentrations of Hg were discovered in Lake St. Clair fish (Fimreite *et al.* 1971) at levels which resulted in implementation of a ban on commercial fishing in that lake in 1970. The source of Hg to Lake St. Clair was upstream chlor-alkali plants on the St. Clair River. In 1971, the Michigan Public Health Department issued a warning on PCBs in lake trout and salmon in Lake Michigan. Soon thereafter, in 1974, Mirex was discovered in fish in the Bay of Quinte, Lake Ontario. In late 1979, chlorinated dioxins were detected in herring gull eggs from colonies in Saginaw Bay, Michigan. In 1982, toxaphene was first detected in fish from Lake Superior. Between these major chemical crises, subsequent sampling revealed that most of these same chemicals were found throughout the Great Lakes system. Also, analyses of Great Lakes media for toxic metals such as Pb and Cd, showed that these were also ubiquitous pollutants of the system. Thus the scientific and public awareness of the level of toxic chemical pollution of the Great

Lakes has developed over a period of some 25 years from DDT; to Hg; to PCBs; to Mirex; to dioxins; to toxaphene. The period of greatest public concern was around 1980 and related to the discovery of 2,3,7,8-TCDD, in herring gull eggs. Another major event occurred in 1985 with a perchloroethylene spill into the St. Clair River.

Chemical analyses of radiodated sediment cores was eventually to show that the serious toxic chemical pollution of the Great Lakes began only after World War II, with the expansion in urban and industrial development. PAHs were detected in lake sediments deposited at the turn of the century. Some chlorinated organics such as PCBs and chlorinated benzenes (CBs) were produced before the war. However, peak input of these compounds and chlorinated pesticides took place much later in the fifties, sixties and early seventies. During the 1970s, more discoveries were made of organochlorine pesticides in bottom sediments. Analyses concentrated on DDT and PCBs. By the late seventies and early eighties, the development of advanced analytical capabilities resulted in a seemingly continuous discovery of additional toxic organic chemicals in the lakes.

DDT use was curtailed in 1970 in Canada and 1972 in the U.S. PCBs were used for electrical capacitors, transformers and plasticizers. Their industrial use was widespread and they were banned in 1979 in the U.S. except for special permit use. HCB and HCBD were used as pesticides and fungicides. They are also by-products of the chloralkali industry and are used in the production of synthetic rubber. Mirex was an insecticide used to control fire ants and as a flame retardant. It is primarily confined to the Niagara River and downstream. Other organic compounds such as dioxins and volatile chlorinated organics are associated with the effluents of petrochemical and pesticide plants or with urban areas. The metals Pb, Hg, and Cd have a wide variety of industrial uses from anti-knock agents in gasoline, to paints, to pesticides, to electroplating. Pb, Hg, and Cd have well established effects on humans, including birth defects, brain damage and can result in death. DDT, PCBs, HCB, HCBD, Mirex, Pb, Hg, and Cd bioaccumulate in fish, wildlife and humans. Most of the chemicals discussed in this report are found in all five Great Lakes.

Sampling and Analysis

The chemicals mentioned here are those which have caused most public concern about contamination of the lakes. However, they have also been those traditionally analyzed for in most media because of the evolving state of analytical methodology. Recent attempts to calculate mass balances for the Great Lakes have revealed that the data bases are quite inadequate, with the possible exception of PCBs (Strachan and Eisenreich 1988).

Since about 1979, the collection of suspended particulates has permitted detection of toxic metals and hydrophobic toxic organic chemicals. Historically water column concentrations and trends have been assessed more commonly by analysis of suspended solids, for example, in the connecting channels such as the Niagara River. However, at the low suspended solids concentrations common in the Great Lakes system, even the most hydrophobic organic chemicals are primarily in the dissolved phase.

It should be clearly stated that reliable quantitative data for toxic contaminants in water are scarce. Nearly all historical results were below then existing detection limits. Concentrations in water are often an order of magnitude or more beneath detection levels in routine sample volumes of 1 to 2 litres. Only since 1980 has it been possible to determine some of these chemicals in water in the open lakes and connecting channels. Large volumes of water (200 litres) are now extracted to detect concentrations in the low ppt and ppq ranges. Measurements of ambient concentrations of toxic metals and organic chemicals in water are complex and have become semi-routine only since 1983. Because of these complex, time consuming and costly procedures for sample collection, preparation and analyses, few measurements for toxic organic chemicals have been made in all parts of the Great Lakes. The values for whole water and especially for the dissolved phase are highly variable in space and time and must still be viewed with caution as they were and still are often near limits of analytical detection.

The requirements to detect extremely low water concentrations has been driven mostly by an objective to (1) understand the relationship of chemical concentrations in water to those in fish; (2) include the several orders of magnitude higher concentrations of these chemicals in bottom sediments in cause-effect linkages; (3) quantify the burial of chemicals in lake sediments as a self-cleansing process; and (4) model chemical fate or concentrations for mass balances so as to determine major sources of toxic chemicals and prioritize control actions.

Concentrations in waters and suspended solids of the Great Lakes can change rapidly depending on sources, bottom sediment resuspension, internal productivity, currents and a variety of other seasonal and limnological processes. In nearshore areas and in the connecting channels, concentrations of chemicals in water and suspended particulates can vary considerably over short periods of time.

The existing expertise over the past eight years has been focused either on priority areas such as the Niagara River or on priority chemicals such as dioxins. By necessity, much of the ambient toxic chemical concentration measurements in abiotic media have gone to detect sources of toxic chemicals along the lower Great Lakes connecting channels. The aim has been to detect which types of chemicals are present, their major sources and their downstream transport to the lower Great Lakes (NRTC 1984; UGLCCS 1989).

Much of the historical dissolved metals data on water from the open lakes has recently been questioned. Metals are ubiquitous and found in sampling platforms such as boats, and in laboratories in dust. Thus, there is increasing evidence for Pb and Cd, but also for the other metals, that the historical water concentrations are an artifact of contamination during sampling and analyses rather than true ambient levels. This means that the true water phase toxic metal concentrations in the Great Lakes are probably far lower than was previously thought or reported. Because of these analytical developments, there are questions as to the validity of comparison of historical with recent concentrations in water.

The bottom sediment and most suspended solids chemical data which follow is considered reliable. Sectioned, radiodated sediment cores have revealed long term trends in chemical inputs to the lakes. These trends can be extended to pre-industrial and even pre-colonial periods.

Given the above brief overview of the toxic chemical contamination of the Great Lakes; the availability of data in different abiotic media; and the problems described for the dissolved phase; the chemicals to be discussed here fall into two general categories :

1) Toxic chemicals for which there is a reasonably extensive data base. These are usually the chemicals which have been those of greatest significance in the development of our knowledge of the extent of contamination of the complete Great Lakes systems. They include Pb, Hg, Cd, and As, DDT and metabolites, dieldrin, BHCs, HCB, Dioxins, and PCBs

2) Toxic chemicals for which there is a data base but which is restricted geographically because the chemicals were associated with some particularly serious sub-area of contamination e.g. the Niagara River. Such chemicals include: CBs (e.g. Lake Ontario); toxaphene (e.g. Lake Superior); octachlorostyrene (OCS) (e.g. Lake St. Clair); Mirex (e.g. St. Lawrence River); chlorinated volatile organics (e.g. the lower Great Lakes and Connecting channels); and PAHs (e.g western Lake Erie).

Toxic Chemicals in Water, Suspended Solids and Bottom Sediments of The Great Lakes and Their Connecting Channels

There have been several comprehensive reports of toxic chemicals in various sections of the Great Lakes. Some of these are: Allan *et al.* 1983; Niagara River Toxics Committee Report, (NRTC) 1984; Chau *et al.* 1985; Lawrence 1986; Canada-Ontario Report on the St Clair River 1986; Upper Great Lakes Connecting Channels Study, (UGLCCS) 1989. Information obtained on the concentrations and fate of toxic chemicals in the connecting channels (the St. Clair, Detroit, and Niagara Rivers) and the fate of these chemicals downstream in lakes St. Clair, Erie and Ontario, has added significantly to the rapidly expanded data base.

There have also been several studies which included all or most of the lakes. Between 1968 and 1975, bottom sediment surveys of some metals and organic chemicals were performed on each of the lakes and composite geochemical maps were produced. These were extremely valuable for making comparisons of the pollution status of the lakes. The interpretation of the distributions must, however, be related specifically to the year or years when the samples were collected. This type of survey has not been repeated. During the 1980s, Rossmann (1982, 1983, 1984, 1986, 1988) studied metals in the waters of each of the Great Lakes. He attempted to determine temporal trends and made interlake comparisons. In 1981, Sonzogni and Simmons presented typical concentration ranges for metal and organic chemicals in the water and sediments of the lakes. Mudroch *et al.* (1988) summarized sediment concentrations of some metals and PCBs in each lake. Strachan and Eisenreich (1988) recently attempted to give representative values for toxic chemical concentrations in Great Lake water and sediments. They assessed the best available values in early 1986 when they attempted to calculate mass balances for several toxic chemicals in each lake. Concurrently, Stevens and Neilson (1989) collected large volume (37 to 55.5 L) surface water samples from Lakes Superior, Huron, Erie and Ontario during 1986 and examined them for toxic organic chemicals. The results of these studies appear in the summary tables for each of the Great Lakes and the Niagara River.

Lake Superior

Lake Superior has a greater surface area than any other lake in the world. By volume it represents half of the water stored in all the Great Lakes and is the second largest lake in the world by volume after Lake Baikal in Siberia. The main tributaries to Lake Superior are the Nipigon, St. Louis, Pigeon, Pic, White, Michipicoten and Kaministikquia Rivers. The lake discharges via the St. Marys River. It is primarily surrounded by the forested, Precambrain terrain of the Canadian Shield.

Chemical mass balance calculations have shown that the atmosphere is a major source of contaminants such as PCBs, DDT, B(a)P and Pb to Lake Superior (Young *et al.* 1987). There are several reasons for this. Compared with the other Great Lakes, agriculture, population and industrialization of the Lake Superior basin are much less. This results in lower overall contamination from these sources. Also, the surface of the lake is about 40% of its drainage basin; the precipitation over the lake accounts for more than 50% of the total water input; and the lake has a long residence time combined with rapid circulation and low sedimentation (Chan 1984).

Some of the chemicals of concern in the St. Marys River are PAHs and PCBs. The zone of greatest impact is along the Canadian shore downstream of industrial and municipal discharges.

Chemical Concentrations in Water and Suspended Solids: The historical concentrations of toxic metals and organic chemicals in the waters of Lake Superior are presented in Table 4. As discussed earlier, much of the historical data, especially for metals, has been questioned. Rossmann (1986) compared his 1983 data on concentrations of metals in the dissolved, particulate and total water phases to earlier data for Lake Superior. The results for Pb, Hg, Cd, and As are discussed here. He concluded that the historical data could only be used to determine trends for total Hg and total As. The rate of decline in concentration of mean total As was 28 ppt/year based on data from 1973–1983 (Rossmann 1986). His metal results were all below the IJC Great Lakes Water Quality Objectives. Rossmann and Barres (1988) compared the 1983 results for Lake Superior with similar studies on the other Great Lakes done between 1980 and 1985. Generally, the mean concentrations of Pb, Hg, Cd, and As in dissolved and total water samples of Lake Superior were significantly (0.05 level of significance) less or not significantly different from concentrations in the other Great Lakes. However, the concentration of dissolved As was significantly higher in Lake Superior than Lake Huron. Elevated levels of Pb, Hg and Cd have been reported for harbours and bays of Lake Superior in the 1980s (Simpson 1987; Kirby 1986; Glass *et al.* 1988).

There have been several studies of toxic organic chemicals in Lake Superior. The results are documented in Table 4. The most recent results show (Stevens and Neilson 1989) that concentrations

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	dis.	1963	22	ND	100	14	31	6	27	41	(1) (5)
Pb	dis.	<1986				75					(11)
Pb	part.	1977	7	50	4,700	770	1,700	100			(2)
Pb	part.	1963	22	11	46	25	10	23	2	0	(1) (5)
Pb	part.	<1986				25					(11)
Pb	whole	1975	5			400	200				(4)
Pb	whole	1977	7	<300	3,200	1,500	1,300	1,500			(2)
Pb	whole	<1981		1000	1,500						
Pb	whole	1963	22	ND	130	39	34	29	27		(1) (5)
Hg	dis.	1963	22	ND	56	0.91	18	0	6.9	95	(1) (5)
Hg	dis.	<1986				7					(11)
Hg	part.	1963	22	ND	100	7.6	34	1			(1)
Hg	part.	<1986				3					(11)
Hg	whole	1970–71	226	ND	470	180	130		50		(3)
Hg	whole	<1981		50	100						
Hg	whole	1963	22	ND	120	9.6	34	2	6.9	90	(1) (5)
Cd	dis.	1963	22	ND	12	6.6	3	6	2	64	(1) (5)
Cd	dis.	<1986				20					(11)
Cd	part.	1977	7	2	40	10	10	4			(2)
Cd	part.	1963	22	ND	38	21	10	21	3.9	23	(1) (5)
Cd	part.	<1986				20					(11)
Cd	whole	1977	7	<20	250	120	100	130			(2)
Cd	whole	<1981				<200					(12)
Cd	whole	1963	22	70	44	27	10	27	2		(1)
As	dis.	1963	22	400	900	550	130	520	29	0	(1) (5)
As	part.	1963	22	ND	50	11	25	10	50	91	(1) (5)
As	whole	1969	47	ND	1,000	230			100		(13)
As	whole	1975	5			800	100				(4)
As	whole	1963	22	430	900	560	130	520	29		(1)
As	whole	<1986				600					(11)
tDDT	dis.	<1986				0.1					(11)
tDDT	part.	<1986				0.1					(11)
p,p'-DDT	whole	1963	11	0.01	0.513	0.227	0.169	0.39			(8)
o,p'-DDT	whole	1963	3	0.016	0.195	0.113	0.09				(8)
p,p'-DDT	whole	1986	19		ND				0.007	100	(7)
o,p'-DDT	whole	1986	19		ND				0.007	100	(7)
p,p'-DDE	whole	1963	15	0.007	0.041	0.02	0.009				(8)
p,p'-DDE	whole	1963	17	0.005	0.024	0.012	0.006				(8)
p,p'-DDE	whole	1986	19		ND				0.007	100	(7)
dieldrin	dis.	<1986				0.1					(11)
dieldrin	part.	<1986				0.1					(11)
dieldrin	whole	<1981				<5					(12)
dieldrin	whole	1963	15	0.06	0.412	0.205	0.092	0.21			(8)
dieldrin	whole	1986	19	0.231	0.425	0.3			0.007	0	(7)
α-BHC	dis.	<1986				2					(11)
α-BHC	part.	<1986				0.2					(11)
α-BHC	whole	1963	16	2.694	15.691	7.716	3.02	7.78		0	(8)
α-BHC	whole	1986	19	5.712	10.991	8.069			0.007	0	(7)
lindane	dis.	<1986				0.6					(11)
lindane	part.	<1986				0.1					(11)
lindane	whole	1963	16	0.278	2.255	0.766	0.461	0.684		0	(8)
lindane	whole	1986	19	0.802	1.434	1.092			0.007	0	(7)

Table 4. *(Continued on following page)*

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
mirex	whole	1983	1			0.004					(6)
mirex	whole	1986	19						0.007	100	(7)
toxaphene	dis.	<1986				0.4					(11)
toxaphene	part.	<1986				0.2					(11)
toxaphene	whole	1981				0.5					(9)
B(a)P	dis.	<1986				0.07					(11)
B(a)P	part.	<1986				0.03					(11)
HCB	dis.	<1986				0.01					(11)
HCB	part.	<1986				0.01					(11)
HCB	whole	1983	16	0.011	0.051	0.028	0.01	0.025			(6)
HCB	whole	1983	17	0.01	0.049	0.023	0.009				(8)
HCB	whole	1986	19	0.016	0.04	0.026			0.007	0	(7)
PCBs	dis.	1978				1.3	1.3				(15)
PCBs	dis.	1986				0.55	0.37				(14)
PCBs	dis.	<1986				0.4					(11)
PCBs	part.	<1986				0.2					(11)
PCBs	whole	1978–80	126	0.3	6.4	1.8	0.2				(10)
PCBs	whole	<1981		1	4	<100					(12)
PCBs	whole	1983	16	1.166	5.113	2.363	1.088	1.94			(6)
PCBs	whole	1983	17	0.32	1.07	0.63	0.24				(8)
PCBs	whole	1986	19	0.193	0.578	0.337			0.17	0	(7)

ND : not detected
Sample : whole = whole water; dis. = aqueous phase; part. = suspended particulate phase.
: number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Rossmann 1986. Particulate conc.: ppt=ng/L. Filter: 0.5 μm pore size. Particulate conc. + dissolved conc. = whole water concentration.
2. Eisenreich 1982. Particulate conc.: ppt=ng/L. Filter: 0.4 μm pore size.
3. Chau and Saitoh 1973
4. Poldoski *et al.* 1978
5. Rossmann and Barres 1988. The number presented for "% below detection" actually represents the percent of analyses below the limit or criterion of detection. Particulate concentrations are ng/l.
6. Chan 1984
7. Stevens and Nielsen 1989
8. Baker *et al.* 1985. All samples were from the same site in western Lake Superior.
9. Sullivan and Armstrong 1985
10. Eisenreich 1987
11. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models. Part. conc.: ppt=ng/L. Particulate conc. + dissolved conc. = whole water conc.
12. Sonzogni and Simmons 1981. Typical concentration ranges. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
13. Traversy *et al.* 1975
14. Baker and Eisenreich 1989
15. Capel and Eisenreich 1985

Table 4. Toxic chemical concentrations in Lake Superior water (ppt).

of all detectable organic contaminants in 1986 were slightly higher in the north than the south of the lake, especially in the vicinity of Nipigon Bay, Jackfish Bay, Peninsula Harbour and Michipicoten Bay. Concentrations of CBs, dieldrin, and PCBs were not significantly different from those of Lake Huron and they were consistently ranked lower than Lake Ontario. The mean concentrations of some of the organic contaminants studied by Stevens and Neilson are given in Table 4.

As for most of the lakes and connecting channels, the persistent, toxic, chlorinated organic chemicals analysed and detected most frequently are total PCBs. There are considerable variations in PCB concentrations in lake waters due to ice cover, ice melt, spring overturn and evaporation (Capel and Eisenreich 1985). Capel and Eisenreich (1985) reported mean total PCB concentrations for the centre of Lake Superior as 1.30 ppt (1978); 3.8 ppt (1979); 0.9 ppt (1980). Baker *et al.* (1985) reported mean concentrations of 0.95 ppt (1978); 3.3 ppt (1979); 0.75 ppt (1980); 0.63 ppt (1983). Their overall conclusion was that lake wide PCB concentrations in water are probably decreasing. The results in Table 4 for whole water lead to a similar conclusion. Eisenreich (1987) estimated the decrease from 1978 to 1983 to be 54%. The residence time for PCB's in Lake Superior waters was estimated as 2 to 6 years as opposed to the hydraulic residence time of 170 to 180 years and on this basis a prediction was made that total PCB's would decline in Lake Superior water to about 0.2 ppt by 1990 (Eisenreich 1987). The latest measurements in 1986 were 0.3 ppt in whole water (Stevens and Neilson 1989) and 0.55 ±0.37 ppt in the dissolved phase (Baker and Eisenreich 1989). The highest 1986 values were 0.56 and 0.58 ppt in Duluth-Superior Harbour and South of the Apostle Islands respectively. The higher values reported by Chan (1984) for 1983 (Table 4) may be the result of analytical artifacts.

The concentrations of toxic chemicals in particulates in Lake Superior are given in Table 4. The benthic nepheloid layer for Lake Superior has been described by Baker *et al.* (1985) and Baker and Eisenreich (1989). Rossmann (1986) reported that particulate As concentrations were significantly higher in the eastern region than in the central region in 1983. For analytical and contamination reasons the data presented here for 1977 should not be compared with the data for 1983 to determine trends. Rossmann and Barres (1988) compared the 1983 results of metal particulate concentrations for Lake Superior with similar studies on the other Great Lakes done between 1980 and 1985. Generally, the mean concentrations of Pb, Hg, Cd, and As in particulates of Lake Superior were significantly less, or not significantly different from concentrations in the other Great Lakes. The exception was the concentration of particulate Cd which was significantly higher in Lake Superior than in Lake Michigan.

There are limited data on toxic organic chemicals in suspended solids other than for PCBs. Most concentrations were measured for whole water samples (Table 4). Baker *et al.* (1985) reported DDE concentrations in suspended solids from the nepheloid layer of western Lake Superior in 1983 as 0.005 to 0.024 ppt. They also found that the concentrations of particulate associated PCBs in the benthic nepheloid layer were not that different from those in the epilimnion. In 1980, the range of PCB concentrations in suspended solids was 30 to 2,770 ppb (ng/g) (Capel and Eisenreich 1985). They pointed out that the fraction associated with particulates versus the dissolved phase changed, with time and with depth. By 1986, the particulate associated PCB concentration had dropped dramatically to 33 ±16 ppb (ng/g) (Baker and Eisenreich 1989). Concentrations of some PCBs and some PAHs in Lake Superior were greater in suspended solids collected by sediment traps than when collected by centrifugation (Baker and Eisenreich 1988). This was considered to be related to biological processing of the contaminants. They found that the flux rates of PCBs to the bottom waters of Lake Superior were up to two orders of magnitude higher than the net accumulation rates of PCBs in the bottom sediments, implying high benthic organism recycling rates. Particulate total PCB concentrations could thus be higher than those found in surficial lake bottom sediments. When Lake Superior was stratified, the fraction of total PCB's associated with particulate phases at all depths was around 13–14% (Baker *et al.* 1985). The highest concentrations of particulate PCBs were in the eastern basin of the lake in 1980 (Capel and Eisenreich 1985). In 1986, individual particulate PAH concentrations ranged from less than one to a few hundred ppb (Baker and Eisenreich 1989).

Chemical Concentrations in Bottom Sediments: The most extensive sampling of bottom sediments of Lake Superior was in 1973 as part of multi-year program to map chemical distributions in the surficial bottom sediments of all five Great Lakes. Although individual element distribution maps, particularly for Hg, were published in separate papers, the report by Thomas and Mudroch (1979) released nearly all of the toxic metal and organic chemical distribution maps for all five lakes in one publication. The systematic lake bottom surficial sediment survey of all five lakes has not been repeated. The maps represent the distribution of chemicals in the bottom sediments only for the period when the samples were collected. The top 3 cm of sediment was used in the analysis to produce the maps and these 3 cm can represent quite a different number of years of sediment accumulation depending on the lake and location in the lake. The present day surficial concentrations and

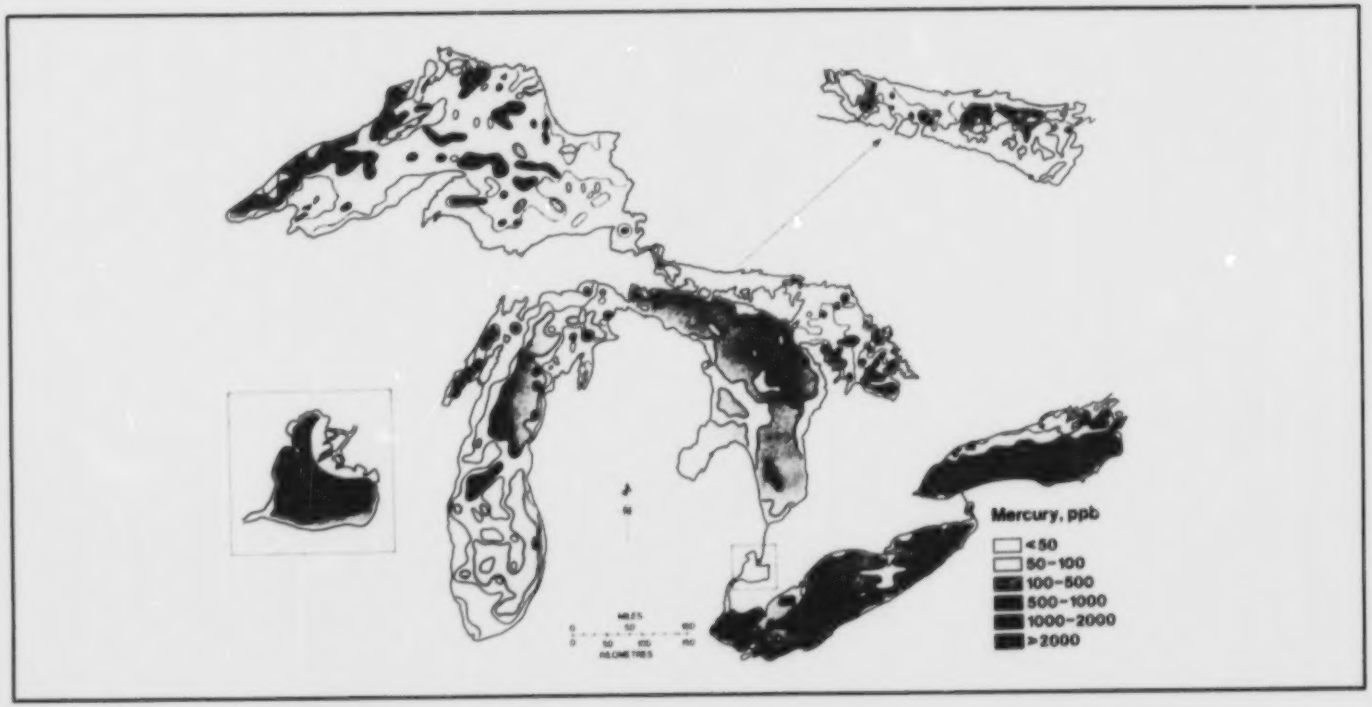
Mercury, ppb
<50
50-100
100-500
500-1000
1000-2000
>2000
MILES
0
50
100
0
50
100
150
KILOMETRES
N

Figure 2. Hg in Great Lakes sediment (Thomas and Mudroch 1979).

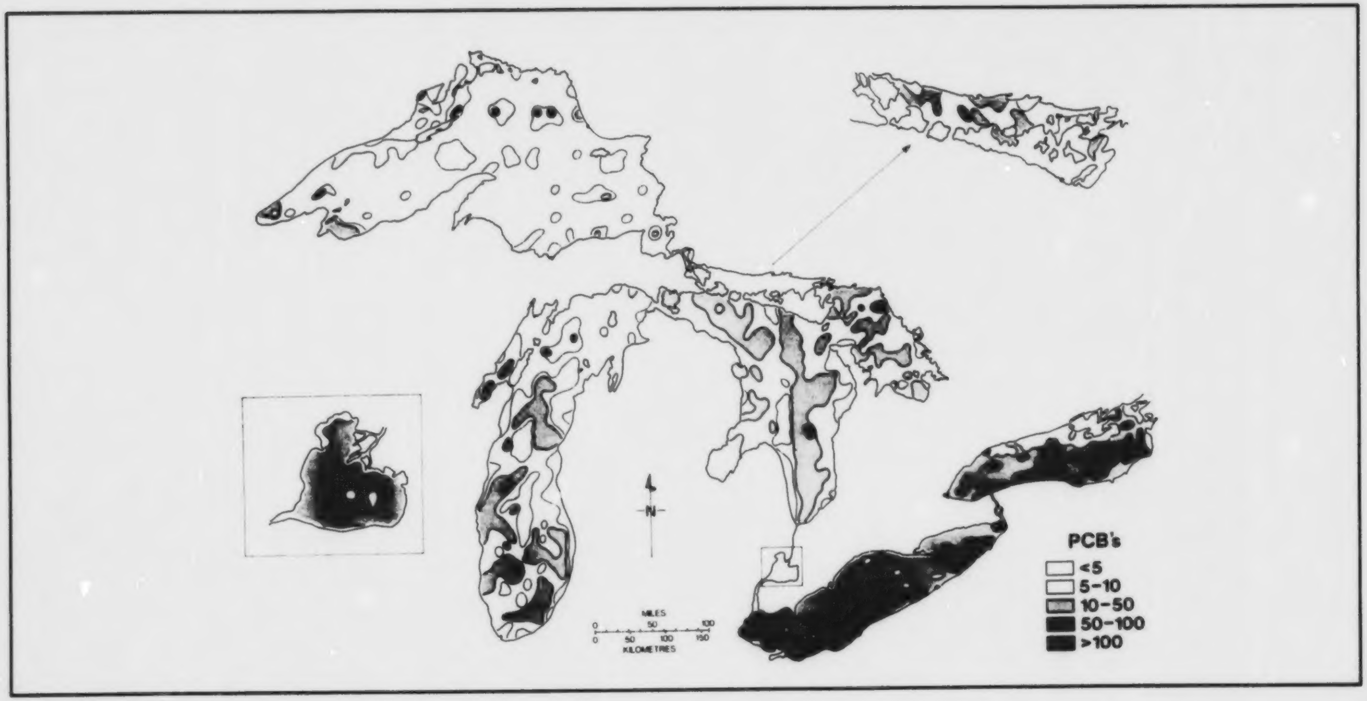
PCB's
<5
5–10
10–50
50–100
>100
N
MILES
0 50 100
0 50 100 150
KILOMETRES

Figure 3. PCBs in Great Lakes sediment (Thomas and Frank 1983).

distributions of toxic metals and organic chemicals will be probably quite different from those represented by samples taken in the late 1960's and early 1970's. Only two example maps for the entire Great Lakes system are included in this report. The first is for Hg which has been considered the most serious metal pollutant of the lakes (Figure 2). The second is for total PCBs, because this is the toxic organic chemical most studied in the Great Lakes system (Figure 3).

In Lake Superior, the concentrations and distributions of metals were principally related to the geology of the area surrounding the lake. Thomas and Mudroch (1979) proposed that the exception was Cu and that concentrations of this metal were related to Cu inputs from mines. Surface sediment concentrations of Pb were usually less than 100 ppm and for Cd less than 4 ppm (Table 5). Information on the As content of Lake Superior bottom sediments showed that the concentrations in the Thunder Bay basin were 2.0 ppm ($n = 15$) with a range of 0.5 to 8.0 ppm in 1973 (Traversy *et al.* 1975). In general, information about As concentrations in Great Lakes sediments is scarce (Mudroch *et al.* 1985).

The distribution of some chlorinated toxic organic chemicals was determined in 1973 bottom sediments (Frank *et al.* 1980) (Table 5). The mean values ($n = 406$) for total PCB and p,p'-DDE were 3.3 ppb and 0.71 ppb respectively for all basins. Eisenreich *et al.* (1980) sampled Lake Superior bottom sediments in 1977 and 1978. Whereas Frank *et al.* (1980) analysed the top 3 cm, Eisenreich *et al.* (1980) concentrations are for the top 0.5 cm only. Eisenreich and Baker (1989) reported that the mean total PCB concentration in 1986 (8.6 ppb) was significantly lower than that of 1978 (74 ppb). This reflects lower PCB burdens in the water column. The mean HCB concentration of 0.2 ppb in surficial sediments in 1980 was at least an order of magnitude lower than in lakes Huron, Erie and Ontario (Oliver and Nicol 1982). In 80 samples collected in 1973, Frank *et al.* (1980) did not detect Mirex at a detection limit of 0.3 ppb. PAH concentrations in sediments are about ten times lower than the other Great Lakes reflecting both its remote location and the primarily atmospheric source (Baker and Eisenreich 1989).

Historical trends in toxic metal loads to Lake Superior have been investigated by collection, sectioning, age dating, and analysis of lake bottom sediment cores. Kemp *et al.* (1978), calculated sediment enrichment factors for several metals in Lake Superior. The mean values for Pb, Hg, Cd, and As were 4.6, 1.8, 2.9 ($n = 6$) and 0.7 ($n = 1$) respectively. The sediment enrichment value is the ratio of the surficial sediment concentration to the historical, pre-settlement concentration below the Ambrosia horizon. Cores analyzed by Rossmann (1986) show that there has been an increase

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	1973	404			44,000	27,000				(11)
Pb	1 cm	1973	5	74,900	143,900	120,000	25,607	133,400			(1)
Pb		<1981		<50,000	150,000	50,000					(8)
Pb		<1984		74,900	138,210						(10)
Pb		<1986				100,000					(9)
Hg	3 cm	1973	404			83	56				(11)
Hg	1 cm	1973	5	94	356	190	91	160			(1)
Hg		<1981		30	300	100					(8)
Hg		<1984		94	160						(10)
Hg		<1986				100					(9)
Cd	3 cm	1973	404			1,200	800				(11)
Cd	1 cm	1973	5	1,400	2,500	2,200	445	2,500			(1)
Cd		<1981		500	2,500	1,000					(8)
Cd		<1984		1,400	2,500						(10)
Cd		<1986				600					(9)
As	3 cm	1973	404			1,700	2,500				(11)
As	3 cm	1973	15	500	8,000	2,033	2,429	800			(2)
tDDT		<1986				8					(9)
p,p'-DDE	3 cm	1973	405	ND	23	0.71	1.65		0.25	66	(5)
DDE	3 cm	1983	6	2.2	7.6	4.6	1.9				(3)
dieldrin	3 cm	1973	405	ND	1.9	<0.25			0.25	95	(5)
dieldrin		<1986				20					(9)
α-BHC		<1986				0.8					(9)
lindane		<1986				0.1					(9)
B(a)P			1			28					(7)
B(a)P		<1986				30					(9)
B(a)P		1986	3	32	40	45	14				(12)
HCB	3 cm	1980	13	0.02	0.7	0.2					(4)
HCB	3 cm	1983	6	0.7	1.8	2.4	0.4				(3)
HCB		<1986				0.2					(9)
HCBD	3 cm	1983	6	0.1	0.1	0.1					(3)
PCBs	3 cm	1973	405	ND	57	3.3	5.7		2.5	78	(5)
PCBs	0.5 cm	1977–78	18	5	390	130	110				(6)
PCBs		<1981				200					(8)
PCBs	3 cm	1983	6	14	53	27	12				(3)
PCBs		<1986				30					(9)
PCBs		1986	3	5.32	11.73	8.62	2.62				(12)

ND : not detected
Sample : depth of surficial sediment sample
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Kemp *et al.* 1978
2. Traversy *et al.* 1975
3. Bourbonniere *et al.* 1986
4. Oliver and Nicol 1982. Depositional and non-depositional zones.
5. Frank *et al.* 1980a. Depositional and non-depositional zones.
6. Eisenreich *et al.* 1980
7. Eadie 1984

Table 5. *(Continued on following page)*

8. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
9. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
10. Mudroch *et al.* 1988. These numbers are a summary of concentration ranges taken from reports published between 1974 and 1984. Concentrations are from surface samples of deposititional zones.
11. IJC 1977c
12. Baker and Eisenreich 1989

Table 5. Toxic chemical concentrations in Lake Superior bottom sediments (ppb).

in Pb concentrations in the most recent sections of sediment cores (Figure 4). Because most Pb introduced to Lake Superior comes from the atmosphere, it is likely that concentrations in the surface sediments will now decline as they have, for example in Lake Ontario (Rossmann 1986). Anthropogenic enrichment of Pb in Lake Superior has been less than for the other Great Lakes (Hodson *et al.* 1984). Concentrations of Hg reached peak values at a depth of 3 cm and decreased to the surface (Figure 4).

The distribution of PCBs in sediment cores for 9 sites in Lake Superior was described by Eisenreich (1987). Each of the top 1 cm of sediment represented approximately 10 years of time. At all sites, the concentrations of PCBs began to increase at a depth corresponding to the late 1940's. Peak concentrations varied at each of the sites but were either at the very surface or at a depth of 1 cm representing a time in the early 1970's. In general, Lake Superior has the lowest sedimentation rate of all of the Great Lakes (Thomas and Frank 1983). In 7 of the 9 cores, the top 0.25 cm had concentrations of total PCB that were 20 to 100% less than the next 0.25 cm section. This could be evidence of a recent decrease in the sedimentary PCB flux. The mean value for the whole lake in the top 0.5 cm was 53 ppb total PCBs. Charles and Hites (1987) determined the average PCB concentration as a function of year in three sediment cores from Lake Superior (Figure 4). The distribution shows a slow increase from around 1943 to 1955; a rapid rise from 1955 to a peak value of 110 ppb in 1972–73; followed by a decline to 75 ppb by 1975. This decline should continue as North American bans and restrictions on PCBs take greater effect. Most of the PCB input to Lake Superior is from the atmosphere (Strachan and Eisenreich 1987).

The historical distribution of some PAHs in Lake Superior sediment cores show that inputs of these chemicals to the lake began after the turn of the century. The highest B(a)P concentration in a Lake Superior core was around 30 ppb at a depth of 0.25 cm

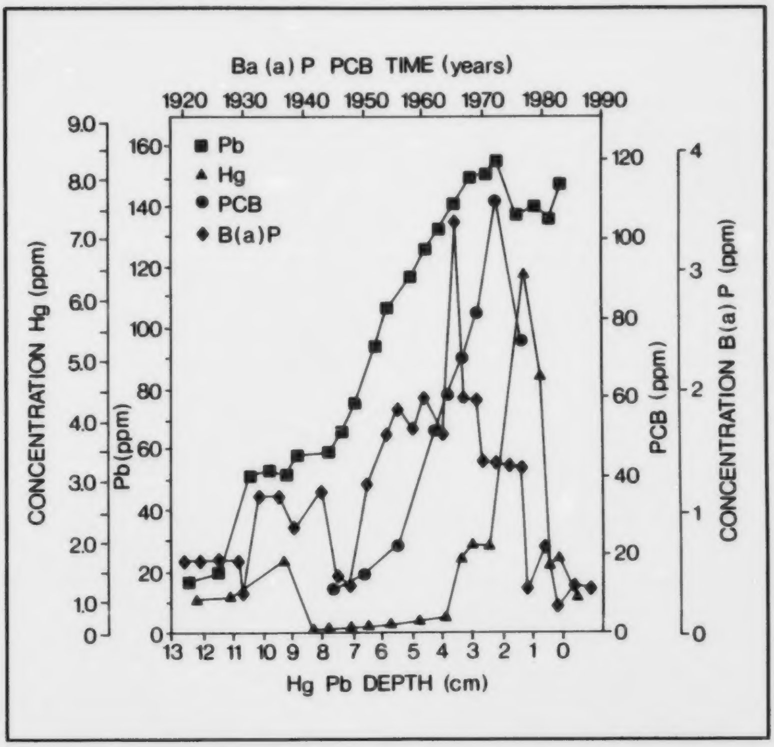

Figure 4. Distribution of Hg, Pb, PCBs in Lake Superior and B(a)P in Lake St. George sediment cores. (After Rossmann 1986; Charles and Hites 1987; UGLCCS 1989.)

(Gschwend and Hites 1987). Although B(a)P concentrations in Lake Superior bottom sediments more than tripled between 1900 and 1980, concentrations are still an order of magnitude lower than in the lower Great Lakes because the region around Lake Superior is far less industrialized (Eadie 1984). In Lake George, part of the St. Mary's River connecting channel between Lake Superior and Lake Huron, B(a)P concentrations in sediment cores show recent declines (Figure 4).

Lake Michigan

Lake Michigan is the only Great Lake to lie completely within the United States. It is the sixth largest lake in the world both by area and volume. Downstream, it is connected to Lake Huron by the Straits of Mackinac. The lake is essentially two basins, a southern basin with depths to 170 m and a northern basin with depths to 280 m.

Lake Michigan and Lake Ontario were the two most contaminated Great Lakes based on combined historical contamination by toxic metals, toxic chlorinated pesticides, and industrial toxic organic chemicals, especially Pb, Cd, DDT and PCBs. The contamination of Lake Michigan by organochlorine chemicals began, as for the other Great Lakes in the 1920's and 30's but increased rapidly after World War II. Contamination of the southern end of the lake has been more severe than the northern end.

One of the main tributaries of the lake is the Fox River which empties into Green Bay. The bay is about 8% of the surface area of the lake but it has about one third of the lakes's watershed (Harris *et al.* 1987). There has been concern about water quality in Green Bay since the 1920s.

Chemical Concentrations in Water and Suspended Solids: Published data on chemical concentrations in Lake Michigan waters are given in Table 6. Historical data on total Pb concentrations in Lake Michigan waters as determined by many investigators was reviewed by Rossmann (1984). The values for both total Pb and dissolved Pb as determined by Rossmann in 1981 are much less than many of the historical levels measured in the 1970s and 1960s because of sample contamination problems. The mean values obtained by Rossmann of 260 ppt total Pb and 150 ppt of dissolved Pb ($n = 11$) are considered the most realistic. Earlier measurements of total Pb had ranged up to 170 ppb with a mean of 18 ppb ($n = 30$) in 1976 (Wisconsin Electric Power Company and Wisconsin Michigan Power Company 1977, in Rossmann 1984). Reported historical mean Hg values were as high as 4.3 ppb (Rossmann 1984) but these earlier values are now considered in error. Essentially all of the Cd measured by Rossmann in 1981 at 11 sites was in the dissolved phase. Earlier mean Cd values as high as 2,800 ppt ($n = 42$) in 1974 are now considered erroneous. In the late 1970's, Owen and Meyers (1984) reported total Cd in the mid-lake subsurface as 70 ppt and nearshore subsurface as 80 ppt. In southern Lake Michigan, the mean concentration of total Cd was 26.6 ppt with a range of 12.0 to 45.6 ppt (Lum 1987). These values are similar to Rossmann's (Table 6). Historic As concentrations were considered by Rossmann to be valid for comparison with recent results. Values of just over 1,000 to 2,000 ppt were measured in the mid to late 1970's and compared to Rossmann's whole water mean value in 1981 of 790 ppt. Much higher values for mean total As were reported prior to 1970 (up to 40 ppb in 1969) but these were almost certainly analytical artifacts.

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	dis.	1981	11	23	270	150	80	14	33	9	(1),(5)
Pb	dis.	<1986				150					(8)
Pb	part.	<1986				50					(8)
Pb	whole	<1981				7000					(3)
Pb	whole	1981	11	130	480	260	110	250	33	0	(1),(5)
Hg	dis.	1981	11	ND	120	44	33	48	26	27	(1),(5)
Hg	dis.	<1986				37					(8)
Hg	part.	<1986				8					(8)
Hg	whole	<1981				<1000					(3)
Hg	whole	1981	11	ND	110	52	31	45	26	18	(1),(5)
Cd	dis.	1981	11	27	190	56	44	45	5.3	0	(1),(5)
Cd	dis.	<1986				20					(8)
Cd	part.	<1986				20					(8)
Cd	whole	1978	17	12	45.6	26.6	9.3	26			(2)
Cd	whole	<1981		<20	3000	<20					
Cd	whole	1981	11	19	87	42	18	44	5.3	0	(1),(5)
As	dis.	1981	11	420	1200	750	260	790	380	0	(1),(5)
As	whole	1981	11	480	1300	790	260	690	380	0	(1),(5)
As	whole	<1986				800					(8)
DDT	dis.	<1986				0.1					(8)
DDT	part.	<1986				0.1					(8)
DDT	whole	<1981				<1000					(3)
dieldrin	dis.	<1986				0.2					(8)
dieldrin	part.	<1986				0.1					(8)
dieldrin	whole	<1981	15			<1					(3)
α-BHC	dis.	<1986				9					(8)
α-BHC	part.	<1986				1					(8)
lindane	dis.	<1986				0.6					(8)
lindane	part.	<1986				0.1					(8)
toxaphene	dis.	<1986				0.4					(8)
toxaphene	part.	<1986				0.2					(8)
toxaphene	whole	<1981				<1					(3)
toxaphene	whole	1981				0.6					(4)
B(a)P	dis.	<1986				0.7					(8)
B(a)P	part.	<1986				0.3					(8)
HCB	dis.	<1986				0.04					(8)
HCB	part.	<1986				0.02					(8)
PCBs	dis.	<1986				1.4					(8)
PCBs	part.	<1986				0.6					(8)
PCBs	whole	<1981				<100					(3)
PCBs	whole	1980	7			6.36	1.3				(7)
PCBs	whole	1980	19	0.4	7.9	1.8	1.8	1.8			(6)

ND : not detected
Sample : whole = whole water; dis. = aqueous phase; part. = suspended particulate phase.
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

Table 6. *(Continued on following page)*

1. Rossmann 1984. Particulate conc.: ppt=ng/L. Filter: 0.5 μm pore size. Particulate conc. + dissolved conc.= whole water concentration.
2. Muhlbaier and Tisue 1981
3. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
4. Sullivan and Armstrong 1985
5. Rossmann and Barres 1988. The number presented for "% below detection" actually represents the percent of analyses below the limit or criterion of detection. Particulate concentrations are ng/L.
6. Swackhammer and Armstrong 1987
7. Eadie *et al.* 1983
8. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models. Part. conc.: ppt=ng/L. Particulate conc. + dissolved conc.= whole water conc.

Table 6. Toxic chemical concentrations in Lake Michigan water (ppt).

Published analyses of Lake Michigan waters for toxic organic chemicals is not extensive (Table 6). From 1968 to 1970, total DDT values were reported as 3 to 151 ppt (Sonzogni and Simmons 1981). Open water samples collected in 1968 and analysed for dieldrin by three independent laboratories reported a mean value for dieldrin of 1.0 ppt. In the late seventies using better detection methods, dieldrin was undetected at 0.1 ppt (Sonzogni and Simmons 1981). Analyses of nearshore samples for toxaphene from 1972 to 1976 failed to detect the chemical at the 1.0 ppb level. The data for PCB concentrations in Lake Michigan waters is more extensive than for other toxic organics because this chemical remains one of the main contaminants of the lake. Rare measurements from the early 1970s, indicated that total PCB concentrations in water may have been from 30 to 40 ppt (Swackhammer and Armstrong 1987). These were probably a result of analytical artifact problems which were not resolved until the early 1980's . Rodgers and Swain (1983) reported water column PCB concentrations of 3 to 9 ppt for 1976. In 1980, Swackhammer and Armstrong (1987) reported an open lake average of 1.2 ppt total PCB, lower than the nearshore average of 3.2 ppt. They found little vertical variability in PCB concentration with lake depth.

Data on toxic chemical concentrations in Lake Michigan particulates is given in Table 6. Rossmann's results (1984) indicated that in the water column, the percentage of Cd and As present in the dissolved and total fractions were such that the particulate fraction did not make a significant contribution to the total concentration.

Chemical Concentrations in Bottom Sediments: The distribution of toxic chemical concentrations is closely related to depositional basins in that concentrations are markedly higher in these basins. Not all of the total metal content is anthropogenic in origin, whereas all of the toxic organic chemicals are. Data on bottom sediment toxic chemical concentrations is given in Table 7. The most extensive surficial sediment survey of Lake Michigan was done in 1975. The distributions of Pb, Hg and As in the surficial sediments were similar. Based on 1973 samples, the concentration range of Cd in surficial sediments was reported as 0.09–1.93 ppm (Cline and Chambers 1977). In northeastern Lake Michigan, the mean value was 0.47 ppm and in Green Bay in northwestern Lake Michigan it was 1.3 ppm ($n = 5$) (Lum 1987). Only very small areas of the lake exceeded 300 ppb Hg (Cahill and Shrimp 1984). The highest values for As were found in Green Bay.

In 1963, early sampling had indicated that some sediments in Lake Michigan had up to 20 ppb of DDE (Hickey *et al.* 1966). In 1975, mean total DDT in surficial lake bottom sediments was 11.9 ppb (Table 7). The mean for the depositional basins was 24.4 ppb ($n = 92$) (Frank *et al.* 1981a). The corresponding mean concentrations for p,p'-DDT, o,p'-DDT, p,p'-TDE and p,p'-DDE were 2.9 ppb and 5.4 ppb; 0.37 ppb and 0.73 ppb; 3.25 ppb and 7.65 ppb; and 5.43 ppb and 10.58 ppb respectively. The distribution of total DDT was similar to that for the heavy metals; that is persistent, hydrophobic organic chemicals are associated with the fine particulate phases which accumulate in the major depositional basins. Most samples had dieldrin concentrations of less than 1.1 ppb. Prior to 1977, dieldrin levels in sediments from southern Lake Michigan of less than 0.5 to 10.4 ppb were reported (Sonzogni and Simmons 1981). Lake Michigan has high sediment concentrations of PAHs (Table 7). In 1979 to 1980, the mean concentration of B(a)P in Lake Michigan sediments from the depositional basins and non-depositional areas was 462 and 62 ppb respectively (Eadie *et al.* 1983). Two major sources of PCBs in the south west part of the lake drainage basin at Milwaukee and at Waukegan are readily discernible from the concentrations in surficial sediments (Figure 3). The mean PCB concentration in the depositional basins of the lake in 1975 was 17.3 ppb (Frank *et al.* 1981a). In Lake Michigan, there are some of the most highly contaminated sites for PCBs in the Great Lakes. They include Waukegan Harbour (500,000 ppm) and North Ditch (250,000 ppm); and Milwaukee Harbour (6.4 ppm)(Simmons 1984).

The distribution of chemicals in sediment cores from Lake Michigan suggests recent decreases in inputs. Lake Michigan has low sedimentation rates which range from 0.1 to 4 mm/year (Cahill and Shrimp 1984). The toxic metal concentrations in sediment cores from Lake Michigan show that pollution with Pb, Cd and other metals

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	1975	266	1,000	153,000	40,000	41,000			3	(3)
Pb		<1981		1,000	150,000	40,000					(1)
Pb		<1984		10,000	130,000						(8)
Pb		<1986				40,000					(2)
Hg	3 cm	1975	266	20	600	107	111			0.7	(3)
Hg		<1981		20	600	100					(1)
Hg		<1984		30	360						(8)
Hg		<1986				100					(2)
Cd	3 cm	1975	266	500	2,500	900	400			66	(3)
Cd		<1981		500	2,500	1,000					(1)
Cd		<1984		50	1,600						(8)
Cd		<1986				1,000					(2)
As	3 cm	1975	266	600	153,000	10,500	16,000			0.7	(3)
As		<1984		5,000	15,000						(8)
As		<1986				11,000					(2)
tDDT	3 cm	1975	266			11.9	16.59		0.1	7	(7)
tDDT		<1981		2	300	20					(1)
tDDT		<1986				50					(2)
p,p'-DDE	3 cm	1975	266			5.43	6.44		0.1	7	(7)
dieldrin	3 cm	1975	266			0.25	0.43		0.1	52	(7)
dieldrin		<1981		<0.5	10	2					(1)
dieldrin		<1986				40					(2)
Mirex	3 cm	1975	62		ND				0.2	100	(7)
PAHs	3 cm	1978		200	6,200						(6)
α-BHC		<1986				1					(2)
lindane		<1986				0.5					(2)
B(a)P		<1983				480	246				(5)
B(a)P		<1986				500					(2)
HCB		<1986				2					(2)
PCBs	3 cm	1975	279			9.7			2	20	(7)
PCBs		<1981		100	200						(1)
PCBs		<1986				200					(2)
PCBs		1980									
OCDD		1982	1			0.96					(4)

ND : not detected
Sample : depth of surficial sediment sample
: number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
2. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
3. Cahill 1981. Depositional and non-depositional zones.
4. Czuczwa and Hites 1986
5. Eadie 1984
6. Helfrich and Armstrong 1986. Southern Lake Michigan.
7. Frank *et al.* 1981a. Depositional and non-depositional zones.
8. Mudroch *et al.* 1988. These numbers are a summary of concentration ranges taken from reports published between 1974 and 1984. Concentrations are from surface samples of depositional zones.

Table 7. Toxic chemical concentrations in Lake Michigan bottom sediments (ppb).

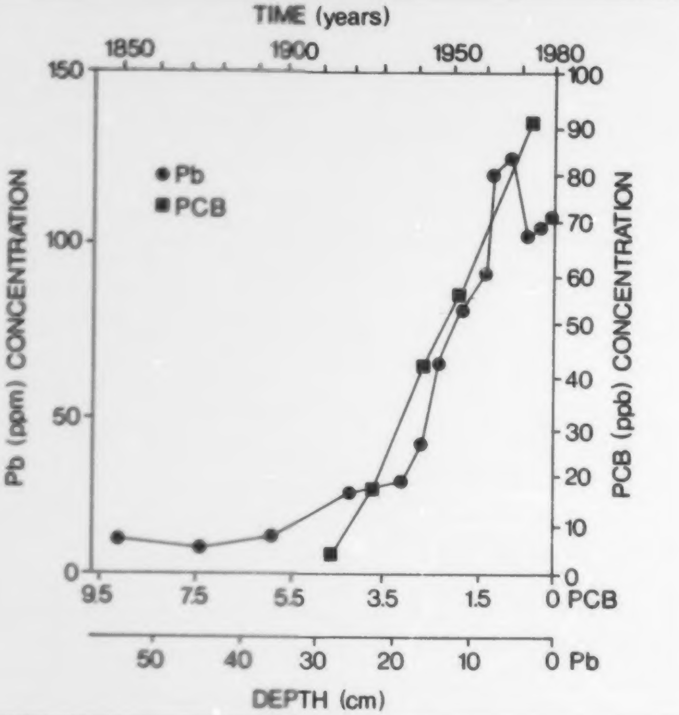

Figure 5. Distribution of Pb and PCBs in Lake Michigan sediment cores. (After Goldberg *et al.* 1981; Swackhammer and Armstrong 1986.)

started in the 1890's in the southern part of the lake and around 1920 further north (Christensen and Goetz 1987). The major increase in Pb (Figure 5) began about 1930 and rose rapidly to a peak between 1960 and 1970. The values in the immediate surface sediments show a decline in Pb concentrations to levels similar to those between 1950 and 1960 (Goldberg *et al.* 1981). This agrees with the period of maximum Pb inputs of 1954–1969 determined by Christensen and Goetz (1987) who calculated that present inputs have declined by 35–45% from these maxima. Maximum Cd pollution occurred between 1939 and 1954 and current levels are 35 to 45% less than these maxima. Goldberg *et al.* (1981) determined the period of maximum Cd input to be in the late sixties. Measureable amounts of PCBs were detected in a core at 3–4 cm depth (Swackhammer and Armstrong 1986). This corresponded to a period from 1920 to 1950 and indicated that inputs to the lake began soon after commercial sales of PCBs in the U.S. in 1929 . The largest flux to the sediments took place between 1960 and the early seventies. Sediment cores have also shown that the initial input of dioxins and furans to Lake Michigan began around 1940 (Czuczwa and Hites 1986).

Lake Huron

Lake Huron is 59,600 km^2 in area. By volume, it is the seventh largest lake in the world and the third largest Great Lake at 3,540 km^3. Its drainage basin is 134,100 km^2. The maximum depth is 229 m and water retention time is 22 years. The major inflows are the Straits of Mackinac and the St. Marys River, followed by the Mississagi, Saginaw, French, and Spanish Rivers. It discharges to the St. Clair River. Manitoulin Island and the Bruce Peninsula divide the body of the lake from the North Channel and Georgian Bay, respectively. The lake is used for both commercial and recreational fishing. The catchment area in 1978 was mainly natural landscape. Toxic chemical inputs to Lake Huron come from municipal point sources, combined sewer overflows, rural and urban nonpoint sources, leachates from municipal and hazardous waste landfill disposal sites and from the atmosphere. Problems related to industrial sources are most apparent in industrialized harbors and embayments such as Saginaw Bay.

Lake Huron has 2 large bays. Saginaw Bay extends 82 km from the main body of the lake. The city of Saginaw, at the head of the bay and on the Saginaw River, was historically a lumbering centre. It now supports agriculture and diversified manufacturing. The bay is used for commercial fishing and summer recreation. Georgian Bay is 190 km long and 80 km wide. The surrounding area is mainly forested with some agriculture in the south. There are several important commercial shipping ports located on Georgian bay.

Chemical Concentrations in Water and Suspended Solids: Toxic chemical concentration data for Lake Huron water is summarised in Table 8. Rossmann (1983) reviewed toxic metal concentrations in Lake Huron. Rossmann (1983) compared his 1980 Pb data to those from previous studies and concluded that the trend in dissolved Pb concentration appeared to be downward. Available data for Hg, Cd and As prior to 1980 could not be used to establish trends. In 1980, dissolved Cd concentrations in Lake Huron were significantly lower than those of lakes Erie and Michigan and there was no significant difference between the Lake Huron levels and those of lakes Superior and Ontario (Rossmann and Barres 1988). Total Cd levels were significantly less than in lakes Erie and Ontario. In Saginaw Bay, very limited data from 1985 suggest that water column values for Pb and Cd were at or below levels measured in 1976–1978 (IJC 1987a). The 1980 dissolved As levels in Lake Huron were significantly lower than those of lakes Michigan, Ontario and Superior but not significantly different from Lake Erie levels (Rossmann and Barres 1988). For total As, Lake Huron median concentration was significantly lower than that of Lake Michigan but not significantly different from that of Lake Erie.

Concentrations of toxic organic chemicals in Lake Huron water are summarised in Table 8. In 1974 and 1975, concentrations of DDT in Saginaw Bay had exceeded the GLWQA objective of 3.0 ppt. However, all subsequent reported concentrations were substantially below the objective level (Kreis and Rice 1985). In a review of historical data, Kreis and Rice (1985) found that all concentrations for the dieldrin-aldrin sum were below the GLWQA objective concentration of 1.0 ppt. A single concentration of 0.5 ppt had been reported for Lake Huron in 1975, considerably below the GLWQA objective of 10.0 ppt. The IJC (1981) reported that toxaphene levels in Lake Superior and Lake Huron water ranged from 0.1 to 1.0 ppt. In Lake Huron the highest PCB concentration of 191 ppt was observed in 1979 at Harbor Beach, Michigan (Anderson *et al.* 1982). The highest PCB concentrations measured in 1980 were in the North Channel (1.56 ppt) and Georgian Bay (1.17 ppt)(Filkins and Smith 1982).

A survey in 1980 was made of toxic metal concentrations in suspended solids in Lake Huron (Rossmann 1982) (Table 8). Particulate Pb levels were somewhat lower in the southern part of the lake and in Georgian Bay than in the rest of the lake. Highest particulate Cd concentrations were found in Georgian Bay and the North Channel. The particulate Cd level in Lake Huron was significantly less than in lake Ontario but not significantly different from lakes Superior and Michigan (Rossmann and Barres 1988). Rossmann (1982) concluded that 100% of the total Cd and 62% of the total Hg were associated with particulate matter. In 1980, particulate As concentrations were highest in southern Lake Huron and in Georgian Bay. Only 3% of the As was in the particulate form.

Most data on toxic organic chemicals in Lake Huron is based on whole water analyses. Some data on particulate concentrations for some toxic organic chemicals is given in Table 8. In 1974, among nine streams sampled around Lake Huron, only one showed unusually high concentrations of total DDT on suspended solids (Frank *et al.* 1981b). That was the Beaver River on the south shore of Georgian Bay with a level of 1.3 ppm . Total DDT in the remaining streams ranged from less than 0.5 to 44 ppb. In 1974 and 1975, the mean

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	dis.	1980	23	ND	81	19	26	6.9	23	71	(2),(5)
Pb	dis.	<1986				150					(1)
Pb	part.	1980	23	ND	140	50	34	41	12	4	(2),(5)
Pb	part.	<1986				50					(1)
Pb	whole	<1981				<1000					(10)
Pb	whole	1980	23	ND	110	38	35	22	34	61	(2),(5)
Hg	dis.	1980	23	ND	360	50	90	4.2	200	87	(2),(5)
Hg	dis.	<1986				7					(1)
Hg	part.	<1986				3					(1)
Hg	whole	1970–71	367	50	380	170	110		50		(6)
Hg	whole	<1981		<40	150						(10)
Hg	whole	1980	23	ND	350	60	92	11	69	61	(2),(5)
Cd	dis.	1980	23	ND	46	3.6	10	0	17	91	(2),(5)
Cd	dis.	<1986				20					(1)
Cd	part.	1980	23	ND	150	21	31	12	0.63	13	(2),(5)
Cd	part.	<1986				20					(1)
Cd	whole	<1981				<20					(10)
Cd	whole	1980	23	ND	61	16	13	15	5.5	13	(2),(5)
As	dis.	1980	23	ND	1750	240	190	250	20	22	(2),(5)
As	part.	1980	23	ND	17	8	4.6	8.6	1.4	61	(2),(5)
As	whole	1969	155	ND	700	410			100	0	(3)
As	whole	1980	23	72	53	250	120	210	14	0	(2),(5)
As	whole	<1986				700					(1)
tDDT	dis.	<1986				0.1					(1)
tDDT	part.	<1986				0.1					(1)
tDDT	whole	<1981				<4					(10)
p,p'-DDT	whole	1980	15	0.01	0.062	0.026	0.013	0.029			(7)
p,p'-DDT	whole	1981	5	0.007	0.027	0.014	0.007	0.01			(7)
p,p'-DDT	whole	1984	16		ND					100	(8)
o,p'-DDT	whole	1984	16		ND					100	(8)
p,p'-DDT	whole	1986	17		ND				0.007	100	(8)
o,p'-DDT	whole	1986	17		ND				0.007	100	(8)
p,p'-DDE	whole	1980	15	0.01	0.09	0.031	0.024	0.021			(7)
p,p'-DDE	whole	1981	5	0.006	0.019	0.013	0.005	0.012			(7)
p,p'-DDE	whole	1984	16	<0.002	0.016						(8)
p,p'-DDE	whole	1986	17	0.018	0.046	0.024			0.007	81	(8)
dieldrin	dis.	<1986				0.2					(1)
dieldrin	part.	<1986				0.1					(1)
dieldrin	whole	<1981				<1					(10)
dieldrin	whole	1984	16	0.197	0.366						(8)
dieldrin	whole	1986	17	0.202	0.686	0.366			0.007	0	(8)
α-BHC	dis.	<1986				9					(1)
α-BHC	part.	<1986				1					(1)
α-BHC	whole	1984	16	4.32	12.19						(8)
α-BHC	whole	1986	17	2.504	10.647	6.16			0.007	0	(8)
lindane	dis.	<1986				0.6					(1)
lindane	part.	<1986				0.1					(1)
lindane	whole	1984	16	0.475	0.835						(8)
lindane	whole	1986	17	0.512	1.416	0.805				0	(8)
mirex	whole	1986	17		ND				0.007	100	(8)
toxaphene	dis.	<1986				0.4					(1)
toxaphene	part.	<1986				0.2					(1)
toxaphene	whole	1980–81				1.6					(9)

Table 8. *(Continued on following page)*

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
B(a)P	dis.	<1986				0.07					(1)
B(a)P	part.	<1986				0.03					(1)
HCB	dis.	<1986				0.01					(1)
HCB	part.	<1986				0.01					(1)
HCB	whole	1980	15	0.003	0.019	0.009	0.005	0.007			(7)
HCB	whole	1980	5	0.02	0.1	0.04			0.01		(4)
HCB	whole	1981	5	0.002	0.007	0.005	0.002	0.004			(7)
HCB	whole	1984	16	0.003	0.032						(8)
HCB	whole	1986	17	0.018	0.073	0.033				6	(8)
PCBs	dis.	<1986				0.7					(1)
PCBs	part.	<1986				0.3					(1)
PCBs	whole	1980	15	0.282	3.232	0.929	0.837	0.572			(7)
PCBs	whole	1981	5	0.135	0.78	0.4	0.234	0.349			(7)
PCBs	whole	<1981		1	10	<100					(10)
PCBs	whole	1984	16	0.076	0.394						(8)
PCBs	whole	1986	17	0.186	2.342	0.631				0	(8)

ND : not detected
Sample : whole = whole water; dis. = aqueous phase; part. = suspended particulate phase.
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985-86. These values were used in mass balance models.
   Part. conc.: ppt=ng/L. Particulate conc. + dissolved conc. = whole water conc.
2. Rossmann 1982. Including Georgian Bay and the North Channel.
   Particulate conc.: ppt=ng/L. Filter: 0.5 μm pore size.
   Particulate conc. + dissolved conc. = whole water concentration.
3. Traversy *et al.* 1975. Excluding Georgian Bay and the North Channel.
4. Oliver and Nicol 1982
5. Rossmann and Barres 1988. The number presented for "% below detection" actually represents the percent of analyses below the limit or criterion of detection. Particulate concentrations are ng/L.
6. Chau and Saitoh 1973. Excluding Georgian Bay and the North Channel.
7. Filkins and Smith 1982. Including Georgian Bay and the North Channel.
8. Stevens and Nielson 1989. The 1986 results exclude Georgian Bay and the North Channel. The 1984 results are based on centrifuged samples and include Georgian Bay and the North Channel.
9. Swain 1978 as quoted in Kreis and Rice 1985
10. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.

Table 8. Toxic chemical concentrations in Lake Huron water (ppt).

levels for total DDT and dieldrin and PCBs were 7.2 and 8.7 ppb; 0.4 ppb and 0.3 ppb, and 36 and 63 ppb. Mirex was not detected.

Chemical Concentrations in Bottom Sediments: Data on toxic chemical concentrations in bottom sediments is presented in Table 9.

In the studies done by both Thomas and Robbins, most Pb concentrations in surficial sediments were less than 100 ppm. Mudroch *et al.*'s (1988) review described surface sediment in depositional basins to have up to 151 ppm Pb with surface

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	1969	197			49,000	34,000				(6)
Pb	1–2 cm	?1969	6	81,300	151,400	123,100	23,000	132,000			(5)
Pb		<1981		50,000	150,000	50,000					(1)
Pb		<1984		3,000	151,400						(3)
Pb		<1986				70,000					(2)
Hg	3 cm	1969	197			217	160				(6)
Hg	1–2 cm	?1969	6	90	297	157	72	122			(5)
Hg		<1981		100	500	200					(1)
Hg		<1984		10	805						(3)
Hg		<1986				300					(2)
Cd	3 cm	1969	197			1,400	3,900				(6)
Cd	1–2 cm	?1969	6	1,400	2,600	2,000	450	2,000			(5)
Cd		<1981		1,000	2,000	1,500					(1)
Cd		<1984		300	4,300						(3)
Cd		<1986				1,000					(2)
As	3 cm	1969	197			1,090	2,160				(6)
As	3 cm	1969	10			2,300	1,100				(4)
As	1–2 cm	?1969	3	19,000	24,000	21,000	2,000	19,000			(5)
As		<1984		14,700	54,000						(3)
As		<1986				5,000					(2)
tDDT	3 cm	1969	174	ND	220	10.2			0.2	2.3	(11)
tDDT		<1981				<30					(1)
tDDT		<1986				40					(2)
p,p'-DDE	3 cm	1969	174	ND	21	3			0.2	6.9	(11)
DDE	3 cm	1980	9	2	15	10					(12)
DDE	3 cm	1980	5	4	28.9	20.6	9	23			(10)
dieldrin	3 cm	1969	174	ND	1.3	<0.2			0.2	94.3	(11)
dieldrin		<1981				<10					(1)
dieldrin		<1986				20					(2)
Mirex	3 cm	1969			ND					100	(11)
Mirex	3 cm	1980	9		ND					100	(12)
α-BHC	3 cm	1980	9		low				0.2	0	(12)
α-BHC		<1986				1					(2)
lindane	3 cm	1980	9		low				0.1	0	(12)
lindane		<1986				0.5					(2)
B(a)P			1			294					(8)
B(a)P		<1986				200					(2)
HCB	3 cm	1980	42	0.4	5	2					(9)
HCB	3 cm	1980	9	0.5	3.3	1.5					(12)
HCB	3 cm	1980	5	1.7	3.1	2.4	0.46	2.3			(10)
HCB		<1986				2					(2)
HCBD	3 cm	1980	9	0.04	0.1	0.08					(12)
HCBD	3 cm	1980	5	0.05	0.6	0.3	0.2	0.3			(10)
PCBs	3 cm	1969	174	3	90	13	10			0	(11)
PCBs	3 cm	1980	9	12	51	34					(12)
PCBs	3 cm	1980	5	64	390	152	121				(10)
PCBs		<1981		<10	>100	100					(1)
PCBs		<1986				100					(2)
OCDD		1975–81	4			0.88					(7)

Table 9. *(Continued on following page)*

ND : not detected
Sample : depth of surficial sediment sample
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
2. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
3. Mudroch *et al.* 1988. These numbers are a summary of concentration ranges taken from reports published between 1974 and 1984. Concentrations are from surface samples of deposititional zones.
4. Traversy *et al.* 1975
5. Kemp *et al.* 1978
6. IJC 1977b. Excluding Georgian Bay and the North Channel.
7. Czuczwa and Hites 1986
8. Eadie 1984
9. Oliver and Nicol 1982. Depositional and non-depositional zones.
10. Bourbonniere *et al.* 1986. Excluding Georgian Bay and the North Channel.
11. Frank *et al.* 1979b. Excluding Georgian Bay and the North Channel. Depositional and nondepositional zones.
12. Oliver and Bourbonniere 1985. Southern Lake Huron. "Low" concentrations: all concentrations were above but close to the detection limit.

Table 9. Toxic chemical concentrations in Lake Huron bottom sediments (ppb).

sediments in embayments to be somewhat higher at up to 230 ppm. Fitchko and Hutchinson (1975) found elevated Pb levels near Parry Sound and in the sediments of the Cheboygan River. Increased concentrations of Hg near the Bruce Peninsula may be due to sphalaerite mineralization (Fitchko and Hutchinson 1975). Mudroch *et al.* (1988) found surface sediment concentrations of Hg in depositional basins to be up to 0.805 ppm and in embayments to be up to 9.5 ppm. Most areas of Lake Huron have Cd concentrations of less than 4 ppm, although a few discreet areas in Georgian Bay have concentrations greater than 6 ppm (Thomas 1981). There was an indication of anthropogenic input to the southern part of the lake but no trends were observed in Georgian Bay. Mudroch *et al.* (1988) found a range of <0.3–4.6 ppm Cd in embayments.

The highest organic chemical residues in surficial sediments from Lake Huron were in Saginaw Bay. Some other nearshore localities also exhibit higher concentrations. In the open lake, the highest concentrations of toxic organic chemicals are in the depositional basins, due to the previously described relationship between hydrophobic organic chemicals and fine-grained sediments. Data on toxic organic chemical concentrations in bottom sediments are given in Table 9. In 1969, Frank *et al.* (1979b) found levels of DDT to be higher in depositional (18.4 ppb) rather than non-depositional zones (3.8 ppb). Of the six basins in Lake Huron, the highest concentrations of DDT were in the Goderich Basin (31.3 ppb). The parent compound was the highest component of DDT followed by DDE and TDE. Although the inputs were primarily from diffuse sources, three point sources were identified as Saginaw Bay, Wasaga Beach, and the central part of eastern Georgian Bay.

In 1969, dieldrin was identified in only 5.7% of the surface sediment samples with residues at or below 1.3 ppb (Frank *et al.* 1979b). Samples containing dieldrin came from the Goderich and Mackinac Basins and in the non-depositional zone near Saginaw Bay. Dieldrin was identified in 30% of the sediments from Georgian Bay in 1973 and 15% of those from the North Channel (Frank *et al.* 1979b). Kreis and Rice (1985) reported that mean dieldrin concentrations were high in Georgian Bay, particularly in Lions Trough and the nearshore zone at Owen Sound. Some samples from Saginaw Bay also showed high concentrations whereas the main lake and the North Channel had lower concentrations. Mirex was not detected by Frank *et al.* (1979b) in 1969 sediments nor by Oliver and Bourbonniere (1985) in 1980. In 1969, unlike DDT, the PCB residues (11 ppb) in the non-depositional zones of Lake Huron were similar to the levels observed in the depositional basins (15 ppb) (Frank *et al.* 1979b). Saginaw Basin contained the highest mean residue (33 ppb) and Alpena Basin the lowest (9 ppb) (Figure 3). The mean concentration for Georgian Bay was 13 ppb while the mean for the North Channel was 8 ppb. In Georgian Bay, substantial inputs of PCBs appeared to come from the northeast shore (Frank *et al.* 1979b). In the review by Mudroch *et al.* (1985), surface concentrations of PCBs ranged from 10–20 ppb in the open lake. In the embayments, they ranged from beneath detection to a high of 490 ppb. Rice and Evans (1984) reported that no data exists for toxaphene in bottom sediments of Lake Huron. In 1981, Czuczwa and Hites (1984) found that concentrations of PCDDs and PCDFs were ubiquitous in 1 cm surface sediment samples and higher closer to urban centres than in the open lake. There was a predominance of OCDD and HpCDF. They concluded that the municipal and/or industrial combustion of chlorinated organic products present in various wastes was probably the source of the dioxins and furans to the Great Lakes. Average OCDD in the surface sediments was 880 ppt (Czuczwa and Hites 1984).

Sedimentation rates in Lake Huron are generally lower than in Lakes Erie and Ontario (Kemp and Thomas 1976a) but higher than in Lake Superior (Thomas 1983). For Pb, Hg, Cd, and As, there has been a marked enrichment at the sediment-water interface relative to low background values. This was related to increasing anthropogenic inputs of these metals to the sediments in recent years or to postdepositional processes (Kemp *et al.* 1978). Robbins (1980), Thomas (1981), and Kemp and Thomas (1976a) all found lead to be consistently enriched in surficial sediments (Figure 6). Surface sediments were also enriched in Cd over background levels (Kemp *et al.* 1978; Kemp and Thomas 1976a; Robbins 1980). Kemp and Thomas (1976a) reported that recent average Cd concentrations (2 ppm) were double that of pre-colonial levels (1 ppm). Robbins (1980) found surficial enrichment of mercury in only a few cores in 1974–75. Most concentrations were less than 0.2 ppm and all were less than 0.30 ppm (Figure 6). In the early 1970s, Kemp *et al.* (1978) found surficial levels of As to be 19–26 ppm corresponding to enrichment factors of 2.7–6.2. Robbins (1980) found As to only occasionally show surficial enrichment in the cores sampled in 1974–75.

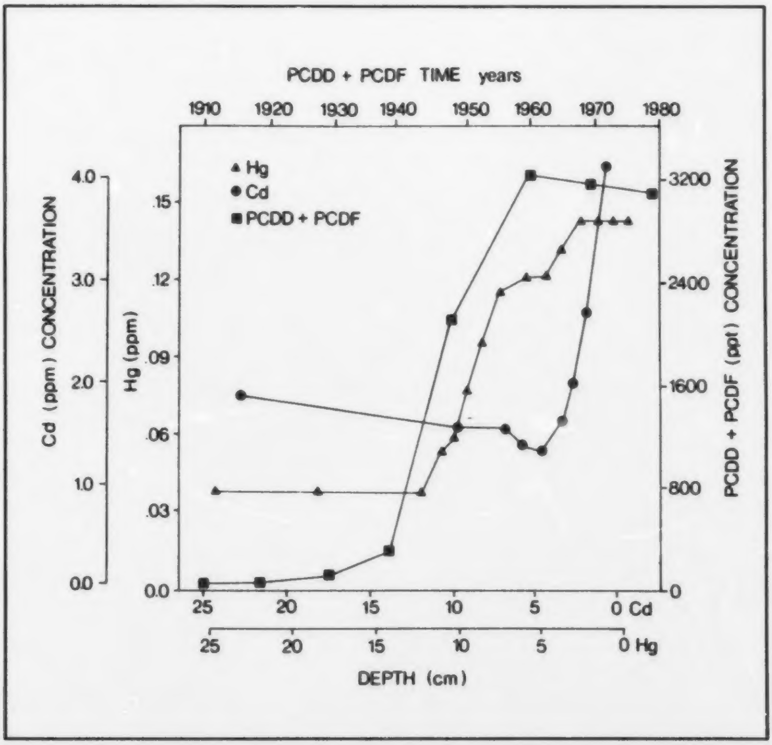

Figure 6. Distribution of Cd, Hg and PCDD + PCDF in Lake Huron sediment cores. (After Robbins 1980; Czuczwa and Hites 1984.)

The resolution of total DDT and PCB profiles in cores proved to be insufficient to provide a good estimate of the onset of their input to the lake but Frank *et al.* (1979b) inferred a period in the early 1950's. Cores analysed by Czuczwa and Hites (1986) indicated that there has been a considerable increase in input of total PCDD and PCDF since around 1940 (Figure 6).

St. Clair River/Lake St. Clair/Detroit River

The St. Clair River drains Lake Huron and flows south into Lake St. Clair. Its length is 64 kilometers. The river is an important international shipping channel and serves as the source of water for commercial, industrial, and domestic uses.

The St. Clair River receives discharges from several refineries and petrochemical plants and the volume of these discharges is about 0.5% of the total river flow (DOE and MOE 1985). The industrial inputs of contaminants are much greater than the municipal ones (Marsalek 1986). The U.S. has 32 permitted discharges to the river, including 6 municipal sewage treatment plants (IJC 1987a). There are 12 industrial and 6 municipal dischargers on the Canadian side of the river. Non-point sources, including contaminated sediments, along with the point sources have led to the degradation of river water and sediments. Many toxic chemicals are confined primarily to a 100 meter wide area along the Ontario shore near Sarnia's chemical industrial area. Contaminants found in elevated levels in sediments include chlorinated organics such as PCBs, and volatile hydrocarbons, and heavy metals, such as mercury and lead. Spills remain a significant problem in this area. Between 1972 and 1984, 175 spills were recorded of which 161 discharged directly into the river or a tributary (IJC 1987b). In 1986 there were 48 spills, 10 of which were on the U.S. side of the river (UGLCCS 1989).

The St. Clair River flows into Lake St. Clair. The average depth of Lake St. Clair is about 3.4 meters. Mean inflow from the St. Clair River accounts for 98 percent of the outflow to the Detroit River. The theoretical flushing time of the lake is 7.3 days. The lake supports the spawning grounds for over 30 species of fish and is one of the most heavily used sport fishing and recreation areas of the Great lakes. Until recently, the lake also supported a commercial fishery.

The Detroit River is a 51 kilometer long connection between Lake St. Clair and Lake Erie. It is used extensively for shipping, recreation and public and industrial water supply. Contamination of the water and sediments by metals and a variety of organic chemicals from municipal, agriculture and industrial waste has led to significant degradation. The majority of the sources, particularly

PCBs, appear to be located along the U.S. shore (UGLCCS 1989). The Rouge River is a major source of contaminants to the Detroit River. Many industrial outfalls, landfill spoil areas, municipal, hydro, and combined sewer facilities are found along the shores of the Detroit River.

Chemical Concentrations in Water and Suspended Solids: There were marginal increases of Pb and Hg along the St. Clair River (UGLCCS 1989). Toxic metal levels were consistently below the GLWQA guidelines except for Pb near Sarnia and Corunna. Elevated levels of alkyllead and Pb were found in the water near Ethyl Corporation, an alkylead production plant at Corunna (Chau *et al.* 1985). Typical Pb and Hg levels in the river are 10–100 ppt and 0.1–1.0 ppb (UGLCCS 1989). In unfiltered water near industrial outfalls, levels of Pb were up to 2.7 ppb in the St. Clair River. Concentrations of Hg in the Detroit River were relatively constant from 1984–1986. Some elevated Hg levels have been reported for tributaries of the Detroit River. Concentrations of Cd did not change significantly over the course of the St. Clair River (UGLCCS 1989). The mean concentration of Cd downstream of the Sarnia industrial area was 10 ppt with a maximum level of 90 ppt. Over the course of the Detroit River in 1987, Cd increased from 23 to 35 ppt and a concentration of 2,060 ppt was recorded in the Rouge River (UGLCCS 1989).

In 1985, very low levels of DDT, dieldrin, α-BHC, and lindane were found in the St. Clair River (Kauss and Hamdy 1985; Oliver and Kaiser 1986; Chan *et al.* 1986). Even distributions indicated non-point sources. No active sources of DDT or metabolites were identified in the Detroit River in 1983 (Kaiser *et al.* 1985). Detectable levels of lindane were reported in Lake St. Clair (UGLCCS,1989). Active sources of dieldrin and lindane have been reported in the Rouge River and the Trenton Channel (Kaiser *et al.* 1985).

Several studies (Kauss and Hamdy 1985; Oliver and Kaiser 1986; Chan *et al.* 1986; Chan and Kohli 1987) have identified point sources of HCB and HCBD near Sarnia. A plume emanating from this area is found along the Canadian shore and exits the river via the Chenal Ecarte. Similar distributions were found in water for QCB and OCS (Chan and Kohli 1987). Mean whole water concentrations above and below the source, in 1985, were 0.03 and 0.8 ppt for HCB and 0.09 and 2.3 ppt for HCBD (Chan and Kohli 1987). The percent of HCB in the dissolved phase was much greater (90%) at the head of the river than at Port Lambton (41%). The percent of HCBD in the dissolved phase at each end of the river was very similar (95% head, 96% Port Lambton). Maximum levels near industrial outfalls on the St. Clair River (unfiltered) were 2.4 ppm HCB and 1.3 ppm

HCBD both of which are much greater than CCREM Water Quality Guidelines of 6.5 ppb and 100 ppb respectively (UGLCCS 1989). Low concentrations were also identified upstream of this major source on the American side of the river (Oliver and Kaiser 1986). The typical range of concentrations reported for HCB in the St. Clair River by the UGLCCS (1989) is 0.1–1.0 ppt.

Concentrations of HCB and HCBD in the mid 1980s were less in water at the head of the Detroit River than at the St. Clair River mouth indicating that some of these contaminants are retained, degraded or volatilized in Lake St. Clair but also that some are carried through to the Detroit River (UGLCCS 1989). CBs concentrations in 1986 were higher in the western basin area of Lake Erie than in southern Lake Huron (Stevens and Neilson, in press). HCB enters the Detroit River from Michigan point sources including the Rouge River (UGLCCS 1989). In 1983, total CB concentrations were highest in the Rouge River and at the mouths of the Trenton Channel and the Detroit River (Kaiser *et al.* 1985). The concentrations were 25.9, 2 and 2 ppt respectively. HCBD was not found in the aqueous phase in the Detroit River. PCBs are ubiquitous in St. Clair River water (Kauss and Hamdy 1985; Oliver and Kaiser 1986; Chan *et al.* 1986). Typical concentrations are 1–10 ppt (UGLCCS 1989). Levels higher than those generally found in the St. Clair River have been observed on the west side at the head of the river (Chan and Kohli 1987). In Lake St. Clair, a mean PCB concentration was reported as 1.2 ppt (UGLCCS 1989). There was no significant difference in concentration between the outlet of the St. Clair River and the inlet for the Detroit River. In 1983, the highest levels of PCBs in the Detroit River were 2.1 ppt at in the Rouge River and 3.4 and 2.1 ppt at the mouth of the Trenton Channel (Kaiser *et al.* 1985). Several industrial volatile halocarbons are present in the Detroit River. High concentrations of these compounds coincide with definite zones of industrial and municipal pollution (Comba and Kaiser 1985). For example, the highest sums of industrial type volatile halocarbons were detected at Connors Creek, 5,121 ppt, just north of Amherstburg, 3,844 ppt, and at the Detroit STP, 3,820 ppt. The concentration range of PAHs in the St. Clair River is 1–10 ppt (UGLCCS 1989). The Sarnia township ditch is a major source of PAHs to the river. In the Detroit River, three major sources were identified in 1983 (Kaiser *et al.* 1985), downstream of major steel manufacturing plants. The two highest concentrations of 6,100 and 5,200 ppt were detected downstream from the Rouge River.

The St. Clair River has a high suspended sediment load dependent largely upon the amount of shore erosion in Lake Huron (Charlton and Oliver 1986). Because Lake St. Clair is shallow, bottom sediments are constantly resuspended by wind events and swept down the Detroit River (Charlton and Oliver 1986).

In 1985, Chan *et al.* (1986) determined concentrations of HCBD, QCB, HCB, and OCS in suspended solids in the St. Clair River. There was a dramatic increase in chemical concentrations in suspended solids over the course of the river. The mean concentrations at the St. Clair River head and at Port Lambton were 2.0 and 130 ppb (ng/g) respectively for HCB. For HCBD, concentrations were 1.0 and 20 ppb. In 1985, Oliver and Kaiser (1986) analyzed water samples near industrial outfalls for HCBD, HCB, OCS, and CBs. The highest concentrations were discovered downstream from the township ditch and near Dow and Polysar. In that area, the concentrations for HCB ranged from 23 to 40 ppm and for HCBD from 9.3 to 24 ppm. These levels are, very roughly, two orders of magnitude greater than levels at the head of the river and downstream. In Lake St. Clair, concentrations of HCB and HCBD in the particulate fraction, were higher in the central corridor of the lake connecting the two rivers (Charlton and Oliver 1986). Mean concentrations in 1985 were 20 ppb for HCB and 4 ppb for HCBD. Elevated levels of total CBs in the particulate phase were found at the head of the Detroit River, 0.9 ppt, downstream of Belle Isle, 2 ppt, and at the mouth of the Detroit River, 1.2 ppt in 1983 (Kaiser *et al.* 1985). In 1985, in Lake St. Clair, the mean particulate concentration of PCBs was 36 ppb (Charlton and Oliver 1986) with higher concentrations consistently on the west side of the lake. In the mid 1970s PCB concentrations in suspended solids were higher in the Detroit River than in Lake St. Clair (Frank *et al.* 1977) and ranked with the Niagara River as the highest levels in the Great Lakes (Frank *et al.* 1981b). The short residence time of the Detroit River may result in an uncharacteristically high fraction of PCBs in the aqueous phase. In 1983, the highest levels of PCBs in the particulate phase, 2.8 ppt, were identified just downstream from Belle Isle and at the mouth of the Trenton Channel (Kaiser *et al.* 1985) and levels were 10 times higher at the Rouge River and Trenton channel than on the Canadian side.

A higher proportion of PAHs than PCBs were associated with suspended solids in the Detroit River, probably because some PAHs enter the river as particles (Kaiser *et al.* 1985). The highest concentrations of particulate PAHs in 1983 were downstream from Belle Isle, 1.3 ppt; adjacent to Fighting Isle, 1 ppt; and at the mouth of the Detroit River, 1.3 ppt (Kaiser *et al.* 1985).

Chemical Concentrations in Bottom Sediments: Sediment accumulation is low in the St. Clair and Detroit Rivers. Less than one percent of contaminant movement is by bottom sediment movement (UGLCCS 1989). Elevated concentrations of certain toxic chemicals were consistently found in the sediments adjacent to the Sarnia industrial complex on the Canadian side of the St. Clair River. A major chemical release happened in 1985 and consisted mainly of perchloroethylene and carbon tetrachloride. Because these chemicals are both volatile, they are only found in sediments near major inputs (Oliver and Pugsley 1986). Elevated concentrations were observed in the river bottom sediments after the spill, mainly on the Canadian side of the river. During the investigation of the 1985 spill, a large area of non-aqueous puddles overlying the sediments was found downstream of Dow (Carey and Hart 1986).

In Lake St. Clair, the area of greatest recent accumulation is in the centre of the lake. However, the sediments are only a temporary reservoir before being resuspended and moved down the Detroit River. Because of the nondepositional nature of Lake St. Clair, the sediments are responsive to changes in loadings. Usage of PCBs, mercury and DDT was curtailed in the early 1970s. Following this, there was a significant decrease in mean concentrations of these compounds between 1970 and 1974 (Thomas *et al.* 1975). Mean Hg concentrations in bottom sediments declined from 1.5 to0.6 ppm; mean DDT from 3.6 to 1.5 ppb and mean PCBs from 19 to 10 ppb. By 1985, the decline in Hg was more pronounced (Figure 7).

Contaminated sediments in the Detroit River occur mainly along the American side of the river downstream from the city of Detroit. The sediment deposited at the mouth of the Detroit River is ultimately resuspended and transported to the depositional zones of Lake Erie.

Lead levels in sediments of the St. Clair River and Lake St. Clair are generally low. Exceptions occur adjacent to (1) the Ethyl Corporation on the St. Clair River where levels up to 339 ppm Pb have been reported in sediment samples, (2) in sediments of the Black River, (3) across the river from the Lambton Generating Station, and (4) in the eastern distributary of the St. Clair Delta (UGLCCS 1989, Mudroch *et al.* 1985).

Pb levels in bottom sediments in the Detroit River are often higher than the dredge spoil guideline of 50 ppm. In 1980, elevated levels were found adjacent to Windsor and along the Michigan side of the river (Hamdy and Post 1985). Concentrations at the mouth of the Rouge River (200 ppm) were higher in 1980 than in 1970 (50 ppm). In two studies done in 1982, the highest levels were found in the southern part of the river (Lum and Gammon 1985; Fallon and

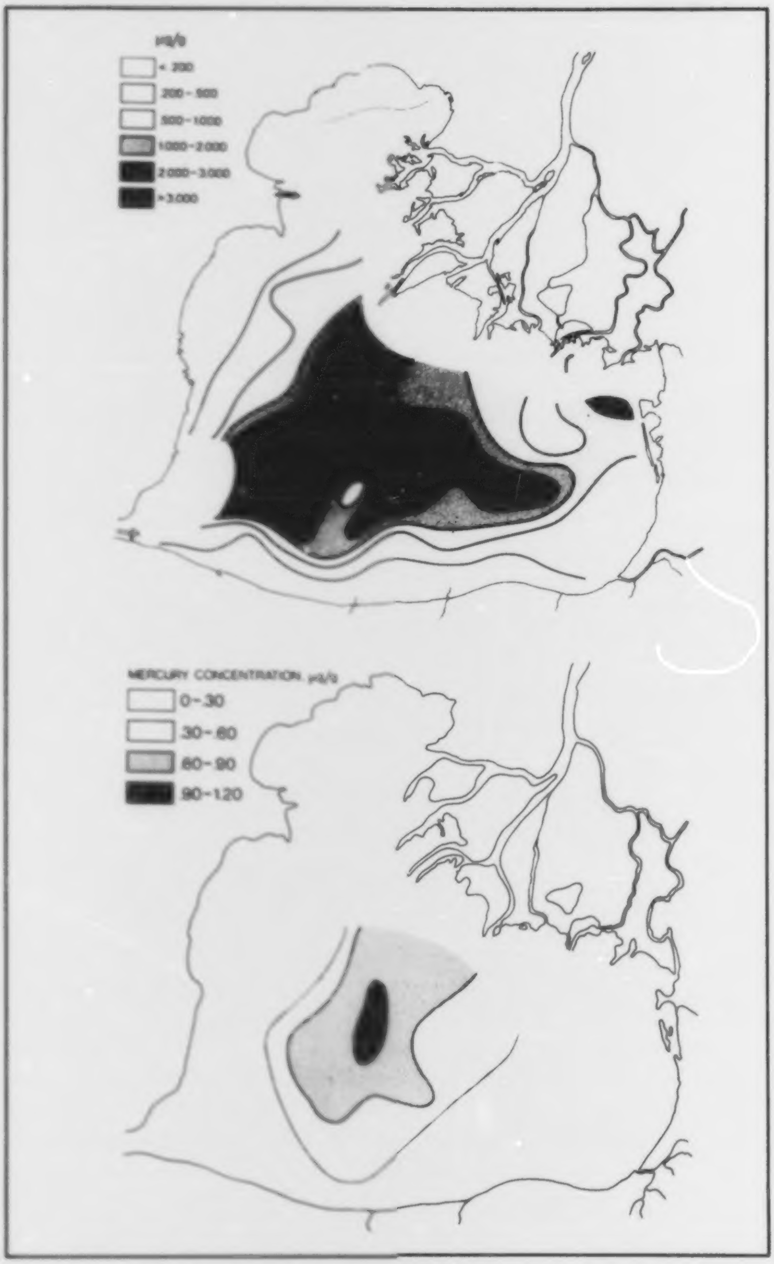
μg/g
< 200
200 – 500
500 – 1000
1000 – 2000
2000 – 3000
> 3000
MERCURY CONCENTRATION μg/g
0 – 30
30 – 60
60 – 90
90 – 120

Figure 7. Distribution of Hg in the surface sediments of Lake St. Clair, 1970 (after Thomas *et al.* 1975) and 1985 (Mudroch and Hill 1987).

Horvath 1985). In 1983, levels of Pb in Detroit River sediments were found to be higher than those of Lakes St. Clair and Erie (Mudroch 1985). The highest concentration (700 ppm) in 1983 was in the surficial sediments at the Rouge River mouth and elevated levels were also found to the west of Fighting Island and Belle Isle. In 1982 and 1985, concentrations of Pb were highest (>200 ppm) in the upper part of the river (above the Rouge River) and in the Trenton Channel (UGLCCS 1989). Some of the maximum levels found in the river have been 960 ppm in 1982 (Lum and Gammon 1985), 704 ppm and 546 ppm in 1983 (Mudroch 1985; Chau *et al.* 1985), and 1,750 ppm in 1982 and 1985 (UGLCCS 1989).

Mercury has been one of the main trace contaminants in this connecting channel. Levels of Hg in the bottom sediments of the St. Clair River peaked in the late 1960s and early 1970s with maximum levels of 1,470 ppm. The main source, the Dow chlor-alkali plant, ceased production in 1973 but some mercury is still entering the river from that area. In the early 1970s, elevated levels were also found at the mouth of the Black River (Fitchko and Hutchinson 1975). By 1977, the concentration at the Dow site had dropped to 58 ppm (IJC 1987a). However, concentrations up to 51 ppm were found in the mid-1980s indicating that inputs remain (UGLCCS 1989). Sediments at the lower end of the river still have concentrations of Hg in excess of dredge spoil guidelines (UGLCCS 1989). Decreases in Hg concentrations in the Detroit River from 1970 to 1980 reflect the reduction of Hg loadings upstream. The upper section of the river, above Zug Island has seen the largest changes in concentrations. The mean concentrations in bottom sediments were 3.73 ppm in 1970 and 0.4 ppm in 1980 (Hamdy and Post 1985). In the mid 1980s, the highest Hg levels in bottom sediments were in the Trenton Channel (>3.0 ppm) and adjacent to Belle Isle (>2.5 ppm) (UGLCCS 1989).

Cadmium in the sediments of the St. Clair River is generally low and not indicative of point sources (UGLCCS 1989). Concentrations of Cd are greater in Lake St. Clair sediments than in Lake Huron sediments (UGLCCS 1989). In 1980, concentrations of >6 ppm Cd were recorded at several locations along the Michigan side of the Detroit River (Hamdy and Post 1985). In 1982, levels of Cd >10 ppm were detected at the mouths of the Detroit and Rouge Rivers (Lum and Gammon 1985). Also in 1982, Fallon and Horvath (1985) reported that the highest concentrations of Cd were at the southern part of the Trenton Channel. In the mid 1980s, peak concentrations of Cd were found adjacent to Belle Isle and the Rouge River and in the Trenton Channel (UGLCCS 1989). Maximum levels ranged from 25 to 96 ppm and continuing sources of Cd to the Detroit River were indicated (UGLCCS 1989).

In 1970 and 1974, the mean concentrations of As in the bottom sediments of Lake St. Clair were 2.5 and 3.4 ppm respectively (Thomas *et al.* 1975). In the Detroit River, the mean concentration of As in the mid 1980s was 10 ppm and the peak level was 54 ppm at the Rouge River (UGLCCS 1989).

In Lake St. Clair, from 1970 to 1974, there was a decline in mean DDT concentrations from 6.6 ppb to 2.4 ppb. The highest concentrations were found at the outlet of the lake at both times. In 1982, Oliver and Bourbonniere (1985) found that mean levels of DDT and metabolites were lower in Lake St. Clair than in southern Lake Huron or Lake Erie.

In 1970 and 1974, 24% of the sediments in Lake St. Clair had detectable levels of dieldrin (Frank *et al.* 1977). In the Detroit river, in 1980, dieldrin was detected in only 22% of the samples (Hamdy and Post 1985) and the maximum level was 35 ppb. In 1985, the highest levels of up to 55 ppb were found adjacent to the Canard River mouth (UGLCCS 1989).

α-BHC and lindane tend to remain in the aqueous phase so sediment concentrations are low. Oliver and Bourbonniere (1985) detected low concentrations in 1982 in southern Lake Huron, Lake St. Clair and Lake Erie. In an earlier study by Frank *et al.* (1977), lindane had not been detected in any samples from Lake St. Clair. In 1980, in the Detroit River, α-BHC and lindane were detected in 52% and 27% of the sediment samples respectively (Hamdy and Post 1985). Concentrations of HCB and HCBD in St. Clair River sediments are reported to be highest in areas adjacent to the Sarnia industrial zone in a 1984 study (Figure 8) (DOE and MOE 1986). For example, concentrations of HCB in bottom sediments near Dow had highest concentrations of up to 24 ppm with average concentrations of 5.2 ppm. Mean concentration of HCB for the reach 35 km downstream was 370 ppb. Maximum HCBD concentration was 46 ppm with a mean concentration of 750 ppb and a downstream level of 190 ppb. Similar results were found in 1985. Concentrations of HCBD in near shore sediments rose from beneath detection to over 1 ppm downstream of the town ditch (Oliver and Kaiser 1986).In 1983, levels of OCS in the bottom sediments were also highest in the area adjacent to the Sarnia industrial complex followed by a plume in Lake St. Clair emanating from the delta (Pugsley *et al.* 1985). Six locations in the river and four in the lake had concentrations of OCS greater than 10 ppb. Oliver and Bourbonniere (1985) reported that in 1982, bottom sediment concentrations of HCB in southern Lake Huron were about 1 ppb and concentrations in Lake St. Clair had a mean level of 68 ppb (top 3 cm). The difference for HCBD was 0.08 ppb in Lake Huron and a mean level of 7.3 ppb in Lake

St. Clair. In 1985, mean concentrations in Lake St. Clair were 21 ppb (top 1 cm) for HCB and 5 ppb for HCBD (Charlton and Oliver 1986). The concentrations of HCB and HCBD in Lake St. Clair are still increasing or at least not dropping significantly (UGLCCS 1989). Elevated levels of HCB, up to 140 ppb, were found in 1985 in the Detroit River adjacent to the Rouge River, in the Trenton Channel and at the mouth of the Detroit River but no major point sources have been identified (UGLCCS 1989). A similar distribution was found in 1983 for total CBs with the exception of a high concentration west of Fighting Island of 3,500 ppb (Kaiser *et al.* 1985).

Mirex was not detected in Lake St. Clair in 1982 (Oliver and Bourbonniere 1985) or the Detroit River in 1980 (Hamdy and Post 1985). Dioxins and furans were detected in the sediment samples in the mid-1980s in the St. Clair River (DOE and MOE 1985, 1986; UGLCCS 1989). Highest concentrations were found at the Township ditch and the 1st Street sewer. The octa- and hepta- congeners predominated and 2,3,7,8-TCDD was not detected.

A review of PCBs in St. Clair River sediments concluded that a trend over time could not be stated because of the variability of the studies (Pugsley *et al.* 1985). In 1983 and 1985, along the Canadian shore of the St. Clair River, there appeared to be an increase in concentrations at the Polysar-Dow area of the river (DOE and MOE 1986) (Figure 8). The maximum levels were considerably higher than the dredge spoil guideline of 0.05 ppm. Additional regions of PCB concern are in the vicinity of Ontario Hydro's Lambton generating station on both sides of the river and in the Belle River (UGLCCS 1989). The range of concentrations along the American shore was relatively low. Oliver and Bourbonniere (1985) did not detect an increase in the concentration of PCBs in sediments between southern Lake Huron and Lake St. Clair. In 1982, mean concentrations of PCBs in Lake St. Clair sediments were much lower than those reported for western Lake Erie (Oliver and Bourbonniere 1985).

The Detroit River is a major source of PCBs to Lake Erie (Oliver and Bourbonniere 1985). PCBs enter the river from Lake St. Clair and there are several point sources along the river. In 1980, PCBs were found in 78% of the bottom sediment samples (Hamdy and Post 1985). The highest concentrations (>500ppb) were found along the Michigan shore south of the city of Detroit. In 1982, the highest levels were found at the head of the river (Fallon and Horvath 1985). This was thought to reflect the effect of Lake St. Clair and a nearby wastewater treatment plant. In 1983, Pugsley *et al.* (1985) reported higher concentrations of PCBs in 10 cm bottom sediments from Lake St. Clair than in the Detroit River. Kaiser *et al.* (1985) found highest concentrations, 200 to 23 ppb, to be at the mouth of the Rouge River,

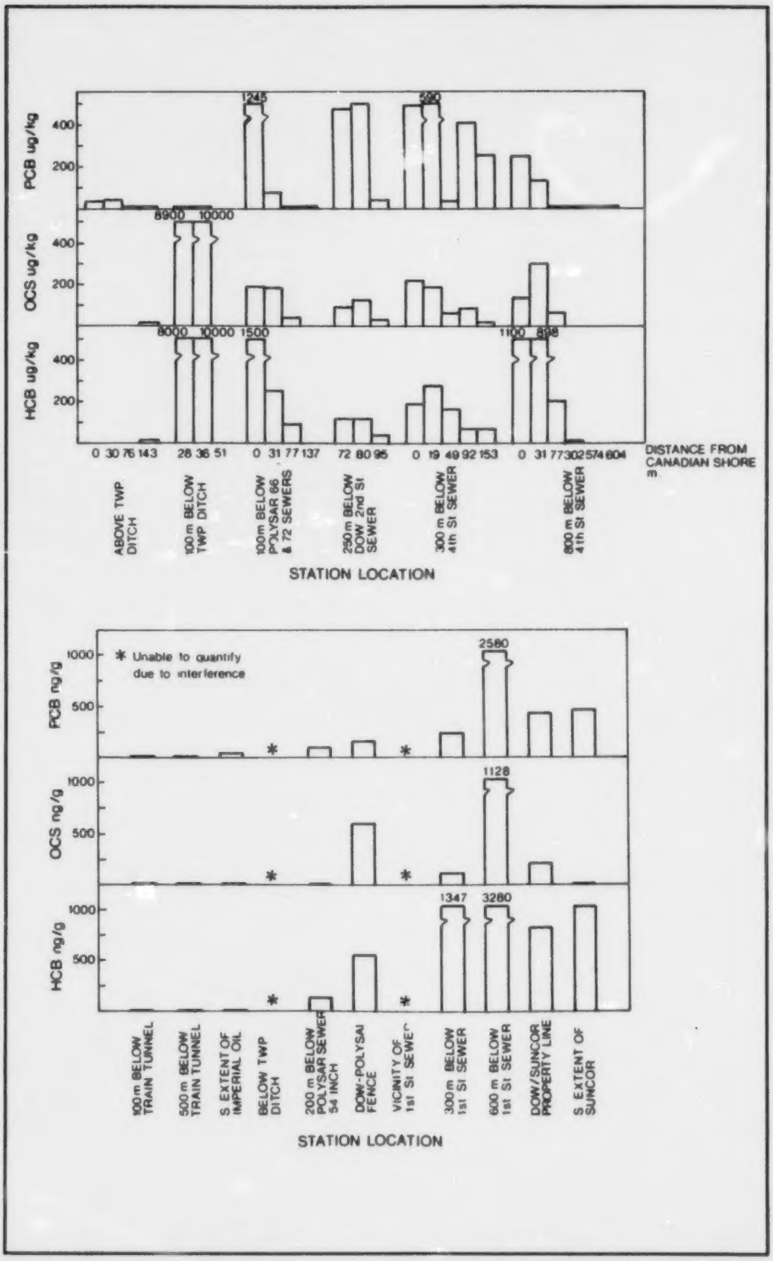

Figure 8. St. Clair River sediment contaminant levels, 1983 and 1985 (DOE and MOE 1986).

southeast of Belle Isle, and at the mouths of the Trenton Channel and Detroit River in 1983. High levels, and possibly sources, are also indicated downstream of Belle Isle (IJC 1987a) and adjacent to the Ecorse River (UGLCCS 1989).

In 1985, PAHs were detected in bottom sediments of the St. Clair River adjacent to Dow at levels up to 60.79 ppm and averaging 3.31 ppm (Nagy *et al.* 1986). Levels up to 140 ppm were reported in the UGLCCS (1989). Elevated levels of PAHs have been identified across the river from Lambton Generating Station and in some tributaries on the American side of Lake St. Clair (UGLCCS 1989). Elevated levels of PAHs were found in the 1980s in the Detroit River, especially downstream of Belle Isle, in the vicinity of Grosse and Fighting Islands, and in the lower Rouge River (Fallon and Horvath 1985; Kaiser *et al.* 1985; UGLCCS 1989). The highest concentrations reported by Kaiser *et al.* (1985) were 20 to 33 ppb. Coal-fired power plants and steel mills are the likely sources.

Most core sample results for this connecting channel system had subsurface maximum concentrations for the chemicals included in this report. Exceptions were Hg in Chenal Ecarte in a 1986 core 1986 (Mudroch and Hill 1987) and HCB and HCBD in the mid-1980s adjacent to Dow (DOE and MOE 1986). Even though concentrations appear to be declining in most cases, surface levels are far greater than background levels. Cores showing surface declines are as follows, by chemical, date of sampling, and geographic location: mercury, 1986, adjacent to Sarnia (Mudroch and Hill 1987); mercury, 1985, central Lake St. Clair (Mudroch and Hill 1987); DDT, 1985, Lake St. Clair (UGLCCS 1989); HCB and HCBD, mid 1980s, vicinity of Dow (DOE and MOE 1986); PCBs, 1985, Lake St. Clair (UGLCCS 1989); and PAH, 1985, St. Clair River (Nagy *et al.* 1986).

Lake Erie

By area, Lake Erie is the fourth largest of the Great Lakes. Lake Erie is the smallest of the Great Lakes by volume and is also the shallowest. It divides naturally into three basins. The western basin, into which the Detroit River flows, is very shallow but has the most important fish spawning and nursery grounds. Downstream from the Canadian chemical companies on the St. Clair River, downstream from Detroit, and with Toledo on its shores, this is the part of Lake Erie most likely to be impacted by toxic chemical contamination. Limnologically, Lake Erie is distinctly different from the other four, deeper and essentially oligotrophic Great Lakes. Lake Erie is mesotrophic and at one time in the 1960's was approaching eutrophic status. Lake Erie has a high nutrient load, relative to its volume. Combined with its shallow depth and high biological productivity, it processes contaminants in a different way from the other four lakes. The greater productivity in Lake Erie may has several possible consequences: the biomass may dilute the chemicals; the organic rich suspended particulates may compete for toxic metals and hydrophobic organic chemicals; the sedimentation and burial rates are higher; and photochemical and biological toxic chemical degradation is perhaps greater. The net result, is that although loads of chemicals such as PCBs to the lake are similar to Lake Ontario (Strachan and Eisenreich 1988), the bioaccumulation of these chemicals has been less.

Lake Erie has been heavily polluted by toxic metals and based on overall metal concentrations, probably comes second to Lake Michigan as the Great Lake most polluted by these contaminants (Rossmann 1984). The relative occurrence of dissolved metal concentrations was highest in Lake Erie (Rossmann and Barres 1988). Lake Erie also had the highest total concentrations of the greatest number of metals.

Chemical Concentrations in Water and Suspended Solids: The summarised data on toxic chemical concentrations in water in Lake Erie is given in Table 10. Rossmann (1984) reviewed the available data for total and dissolved Pb in Lake Erie water. For water collected at unrecorded depths, the 1974 and 1980 medians were at the limit of detection at that time (5 to 10 ppb) ($n = 6$). Total Pb in epilimnion water, taken at depths of less than 5 m, revealed no trend. Mean concentrations in 1967, 1973, 1975, 1978 and 1979 ranged from 0 to 9 ppb. This early data and that in Table 10 cannot be taken as evidence of a decrease in Pb concentrations but rather reflects that true metals concentrations are less than had been estimated by earlier sampling and analytical techniques. Sonzogni and Simmons (1981) arrived at the same conclusion when comparing data from 1967 with that from 1970 to 1977. In 1978, dissolved Pb mean values as high as 23 ppb and a maximum of 840 ppb ($n = 717$) had been recorded. Again, this historical data is unlikely to be accurate (Rossmann 1984). Earlier Hg data from the 1970's recorded mean total Hg concentrations of up to 370 ppt (median 37 ppt and maximum 130 ppb ($n = 618$) in 1978). There may be a trend, for example for total Hg, which was a mean of 170 ppt ($n = 170$) in 1970–71; 370 ppt ($n = 618$) in 1978; 81 ppt ($n = 596$); in 1979; and 42 ppt ($n = 11$) in 1981. Rossmann (1984) calculated that total Hg concentrations in epilimnetic water appeared to be declining at a mean rate of 12 ppt/year. The reason for the changes is more likely the improvement in analytical accuracy. Mean values for dissolved

Cd in 1963 and 1964 were reported as 10 ppb ($n = 49$) (the detection limit). In the 1970's, mean dissolved Cd concentrations were reported as 1.1 ppb (1970; $n = 9$); 0.7 ppb (1971; $n = 112$); 2.5 ppb (1978; $n = 708$); 0.7 ppb (1979; $n = 567$). The latter value for 1979 is still an order of magnitude higher than the mean dissolved concentration of 71 ppt measured in 1981 (Table 10). In 1978, Lum and Leslie (1983) reported that 87% of the total Cd in Lake Erie water was in the dissolved phase. In 1981, Rossmann (1984) found dissolved Cd to be lowest in the waters of the central basin, but insufficient samples were collected to justify this statistically. Lum (1987) compared Rossmann's (1984) data for 1981 (71 ±27 ppt) with his data for 1978 (40 ±20 ppt) and for 1984 (29 ±15 ppt). Because all of this Cd data is considered to be reliable, there may be a decreasing trend, although the differences may still be methodological. For 1975, Rossmann quotes a value of 1.0 ppb ($n = 2$) total As in water from unrecorded depths. In 1980, a mean value of 10 ppb As ($n = 6$) was recorded but in this case this was the detection limit. Mean concentrations in 1981 were about 50% of what mean values were thought to be by measurements made in the late 1970s. Rossmann arrived at a total As rate of decrease of 310 ppt/year between 1978 to 1981.

There is limited data available on the concentrations of toxic organic chemicals in the waters of Lake Erie (Table 10). Nearly all early values were beneath the detection limits prior to the implementations of new sampling and analytical techniques developed in the early 1980's. For DDT, Konasewich *et al.* (1978) reported open lake water values close to or less than the detection of 1 ppt. McCrea *et al.* (1985) using newly developed large water value extraction procedures reported that in 1981 p,p'-DDT was detectable at all of his sample stations and was present almost exclusively in the aqueous phase. Between 1981 and 1983, DDE was detected at concentrations of some 0.1 ppt (Oliver and Nichol 1984). In 1981, Filkins *et al.* (1983) reported p,p'-DDT and p,p'-DDE concentrations ranging from 0.007–0.022 ppt and 0.006–0.018 ppt respectively ($n = 5$). In 1986 Lake Erie surface water DDE concentrations ranged from beneath detection to 0.08 ppt (IJC 1987). For 1981, McCrea *et al.* (1985) reported that 94% of the dieldrin in Lake Erie surface water was in the aqueous phase. Concentrations were reported as between 0.069 and 0.0934 ppt. McCrea *et al.* (1985) reported that 100% of lindane was present in the aqueous phase. At Fort Erie in 1981 to 1983, Oliver and Nicol (1984) reported total concentrations of 4.2 ppt α-BHC and 0.38 ppt γ-BHC. No Mirex was found in waters of the eastern area of Lake Erie by McCrea *et al.* (1985). Eadie (1984) stated that some 90% of the PAH's in the waters of Lake Erie were in the dissolved phase and that only in nearshore

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	dis.	1981	11	ND	500	220	140	170		9	(2),(5)
Pb	dis.	<1986				750					(4)
Pb	part.	1981	11					190			(5)
Pb	part.	<1986				250					(4)
Pb	whole	1978–79				1,180–26,310					(1)
Pb	whole	<1981		<1,000	5,000						(7)
Pb	whole	1981	11	150	3,000	910	1,000	340		0	(2),(5)
Hg	dis.	1981	11	ND	80	34	29	24		55	(2),(5)
Hg	dis.	<1986				30					(4)
Hg	part.	1981	11					2			(5)
Hg	part.	<1986				10					(4)
Hg	whole	1970–71	170	ND	400	170	110		50		(6)
Hg	whole	1978–79				10–730					(1)
Hg	whole	<1981				<1,000					(7)
Hg	whole	1981	11	ND	14	42	44	33		27	(2),(5)
Cd	dis.	1981	11	41	120	71	27	67		0	(2),(5)
Cd	dis.	<1986				50					(4)
Cd	part.	<1986				50					(4)
Cd	whole	1978–79				370–10,660					(1)
Cd	whole	<1981				<200					(7)
Cd	whole	1981	11	39	320	98	81	72		0	(2),(5)
As	dis.	1981	11	ND	800	380	190	420		55	(2),(5)
As	part.	1981	11					87			(5)
As	whole	1969	17	ND	600	250			100	35	(3)
As	whole	1978–79				ND–2,290					(1)
As	whole	1981	11	280	920	490	200	430		0	(2),(5)
As	whole	<1986				500					(4)
tDDT	dis.	<1986				0.1					(4)
tDDT	part.	<1986				0.1					(4)
tDDT	whole	<1981				<1					(7)
p,p'-DDT	whole	1986	21		ND				0.011	100	(8)
o,p'-DDT	whole	1986	21		ND				0.011	100	(8)
p,p'-DDE	whole	1986	21	0.028	0.096	0.053			0.011	48	(8)
dieldrin	dis.	<1986				0.3					(4)
dieldrin	part.	<1986				0.1					(4)
dieldrin	whole	<1981				<1					(7)
dieldrin	whole	1986	21	0.082	1.111	0.402			0.011	0	(8)
α-BHC	dis.	<1986				9					(4)
α-BHC	part.	<1986				1					(4)
α-BHC	whole	1986	21	2.576	6.513	3.962			0.011	0	(8)
lindane	dis.	<1986				2.0					(4)
lindane	part.	<1986				0.2					(4)
lindane	whole	1986	21	0.581	2.554	1.075			0.011	0	(8)
mirex	whole	1986	21		ND				0.011	100	(8)
toxaphene	dis.	<1986				0.4					(4)
toxaphene	part.	<1986				0.2					(4)
toxaphene	whole	1981				0.7					(9)
B(a)P	dis.	<1986				0.2					(4)
B(a)P	part.	<1986				0.1					(4)
HCB	dis.	<1986				0.04					(4)
HCB	part.	<1986				0.02					(4)
HCB	whole	1986	21	0.025	0.26	0.078			0.011	24	(8)

Table 10. *(Continued on following page)*

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
PCBs	dis.	<1986				0.7					(4)
PCBs	part.	<1986				0.3					(4)
PCBs	whole	<1981		1	10	<100					(7)
PCBs	whole	1986	21	0.341	3.513	1.378			0.24	0	(8)

ND : not detected
Sample : whole = whole water; dis.= aqueous phase; part.= suspended particulate phase.
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Rathke 1984. The range represents the mean concentrations for the 2nd to 4th quarters of 1978 and 1979 along the south shore.
2. Rossmann 1984. Particulate conc.: ppt=ng/L. Filter: 0.5 μm pore size. Particulate conc. + dissolved conc.= whole water concentration.
3. Traversy *et al.* 1975.
4. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models. Part. conc.: ppt=ng/L. Particulate conc. + dissolved conc.= whole water conc.
5. Rossmann and Barres 1988. The number presented for "% below detection" actually represents the percent of analyses below the limit or criterion of detection. Particulate concentrations are ng/L.
6. Chau and Saitoh 1973.
7. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
8. Stevens and Nielson 1989.
9. Sullivan and Armstrong 1985

Table 10. Toxic chemical concentrations in Lake Erie water (ppt).

areas is a substantial portion of the low-solubility PAH associated with suspended solids. Near Buffalo, in 1976, B(a)P and total PAH were found at concentrations of 0.3 ppt and 4.7 ppt, respectively (Basu and Saxena 1978).

There are many sources of PCBs to Lake Erie, including industrial and municipal outfalls, land and urban runoff, landfills, resuspension and translocation of contaminated lake bottom sediments and the atmosphere. From 1972 to 1978, five independent groups reported that total PCBs in Lake Erie waters were below the then detection limit of 100 ppt, while one lake-wide survey in 1972 reported a mean value of 27 ppt (Glooschenko *et al.* 1976). Also, a nearshore mean value of 20 ppt was reported for 1974–75 (Konasewich *et al.* 1978). Both of these values were at the then current detection limits (Sonzogni and Simmons 1981). In 1981, McCrea *et al.* (1985) reported that 100% of the PCBs in Lake Erie water were in the aqueous phase. Between 1981 and 1983 at Fort Erie, Oliver and Nicol (1984) detected various PCB isomers at 0.49, 0.46 and 0.25 ppt. Clearly, by the early 1980's, the mid-1970's detection limit of 100 ppt was unfeasible for detection of PCB trends in water. Filkins *et al.* (1983) detected PCBs at 0.13 to 0.78 ppt ($n = 5$). The spatial distribution of PCBs in Lake Erie showed that the highest concentrations of >2.5 ppt PCBs were at the extreme western end of the lake (Stevens and Neilson 1989). Most of the western basin had concentrations higher than found in Lake Ontario. The IJC (1987b) reported surface water PCB values of 0.29–2.96 ppt. If the data for 1972 to 1975 is considered reliable, then the decline from some 23 ppt in the early 1970's to 1986 concentrations of some 1.4 ppt in 1986 could be evidence of a dramatic decrease in PCB concentrations.

Numerous volatile industrial organic chemicals which are present in the dissolved state were determined in lower Great Lake waters starting in the late 1970's. All concentrations were shown to be highest in the western-central basin; for example, levels over 30 ppt carbon tetrachloride were detected in 1978 (Kaiser and Valdmanis 1980). Because those chemicals are volatlized and degrade, continual imputs must occur to maintain these concentrations. Mean concentrations in Lake Erie in 1977 and 1978 were 76 and 73 ppt dichloro-difluoromethane; 34 and 46 ppt trichlorofluoromethane; 15 ppt chloroform; 19 and 37 ppt carbon tetrachloride; and 20 and 11 ppt trichloroethlyene respectively (Kaiser and Valdmanis 1980).

The available data for toxic chemical concentrations in suspended solids is summarised in Table 11. Suspended material in Lake Erie is derived from shoreline erosion, river inputs, aeolian material, autochthonous organic matter production and bottom sediment resuspension. Lake Erie has TSM concentrations of 2–6 mg/L, compared to Lake Ontario (1–4 mg/L), Lakes Huron and Michigan (0.5–2 mg/L), and Lake Superior (0.2–1 mg/L) (Eadie and Robbins 1987). As discussed in the introduction, this may have had and may still exert a profound damping effect on toxic metal and hydrophobic toxic organic chemical bioaccumulation in Lake Erie as compared to the other lakes. Accordingly, as reported by Rossmann and Barres, (1988), Lakes Erie and Ontario had the highest concentrations of toxic metals in the particulate fraction. Lake wide particulate Cd concentrations were 2.4 ppm ($n = 54$) in 1978 and 1984 compared to 1.7 ppm ($n = 14$) measured at the Niagara River inflow at Lake Erie, indicating a retention of some particulate Cd in the lake, most likely in the deep eastern basin (Lum 1987).

Toxic organic chemical measurements in suspended solids are rarer than for toxic metals (Table 10). Most of the concentration data for the toxic organic chemicals was extracted from Strachan and Eisenreich (1988) who carefully reviewed all available published

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	1971	258	9,000	299,000	87,000	50,000				(5)
Pb	1 cm	1971	6	83,000	146,000	107,000	23,000	100,000			(11)
Pb	10 cm	1979		<50,000	>140,000						(13)
Pb		<1981		<50,000	>150,000						(1)
Pb		<1984		6,000	299,000						(3)
Pb		<1986				100,000					(2)
Hg	3 cm	1971	258	8	2,929	576	554				(5)
Hg	1 cm	1971	6	330	1,430	660	340	650			(11)
Hg	10 cm	1979		<300	<2,000						(13)
Hg		<1981		<50	2,000						(1)
Hg		<1984		45	4,800						(3)
Hg		<1986				500					(2)
Cd	3 cm	1971	258	100	10,800	2,400	1,500				(5)
Cd	1 cm	1971	6	2,500	4,500	3,500	720	3,500			(11)
Cd	10 cm	1979		<3,000	>4,000						(13)
Cd		<1981				<8,000					(1)
Cd		<1984		800	13,700						(3)
Cd		<1986				1,000					(2)
As	3 cm	1971	10	2,000	4,000	3,200	1,100	3,200			(4)
As	3 cm	1971	258	200	60,000	1,300	4,300				(5)
As		<1984		450	12,300						(3)
tDDT	3 cm	1971	259	0.6	322	27.9	32.6		0.1–0.2		(14)
tDDT		<1981		20	30						(1)
tDDT		<1986				30					(2)
p,p'-DDE	3 cm	1971	259	0.2	136	8.2	11.4		0.1–0.	0	(14)
p,p'-DDE	3 cm	1982	46	2.6	17	3.6-6					(12)
DDE	3 cm	1982	5	5.7	21	10.7	5.4	9.6			(10)
dieldrin	3 cm	1971	259	ND	5	1.2	0.9		0.2	14	(14)
dieldrin		<1981				<3					(1)
dieldrin		<1986				20					(2)
Mirex	3 cm	1982	46		ND					100	(12)
Mirex	3 cm	1982	5		ND					100	(10)
α-BHC	3 cm	1982	46		low				0.2	0	(12)
α-BHC		<1986				2					(2)
lindane	3 cm	1982	46		low				0.1	0	(12)
lindane		<1986				1					(2)
B(a)P			3			255	152				(6)
B(a)P		<1986				200					(2)
HCB	3 cm	1980	5	0.7	12	3					(9)
HCB	3 cm	1982	5	2.5	20	7.6	6.6	2.6			(10)
HCB	3 cm	1982	46	1.2	17	2.4-9.1					(12)
HCB		<1986				4					(2)
HCBD	3 cm	1982	5	0.1	2.4	0.86	0.64	0.5			(10)
HCBD	3 cm	1982	46	0.1	3.2	0.2-1.6					(12)
PCBs	3 cm	1971	231	4	800	95	114				(14)
PCBs		<1981		<10	>100	100					(1)
PCBs	3 cm	1982	46	37	660	91-300					(12)
PCBs	3 cm	1982	5	150	1099	426	355.3	242.2			(10)
PCBs		<1986				60					(2)
OCDD		1981-83	2	1700	2.0						(7)

Table 11. *(Continued on following page)*

ND : not detected
Sample : depth of surficial sediment sample
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Sonsogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
2. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
3. Mudroch *et al.* 1988. These numbers are a summary of concentration ranges taken from reports published between 1974 and 1984. Concentrations are from surface samples of depositititional zones.
4. Traversy *et al.* 1975
5. Thomas and Mudroch 1979.
7. Czuczwa and Hites 1986
8. Eadie 1984. Adjacent to Raison River in the Western Basin.
9. Oliver and Nicol 1982. Depositional and non-depositional zones.
10. Bourbonniere *et al.* 1986. Excluding Georgian Bay and the North Channel.
11. Kemp and Thomas 1976b
12. Oliver and Bourbonniere 1985. Mean concentrations were given for the Western, Central and Eastern zones.
13. Rathke 1984
14. Frank *et al.* 1977. Depositional and non-depositional zones.

Table 11. Toxic chemical concentrations in Lake Erie bottom sediments (ppb).

and values to select reliable values for use in predictive models. The most recent data relied on is that of Stevens and Neilson (1989).

Chemical Concentrations in Bottom Sediments: Chemical concentration data for Lake Erie bottom sediment is summarised in Table 11. Two studies of toxic chemical concentrations in bottom sediment have been carried out in Lake Erie, one in 1971 (Frank *et al.* 1977; Thomas and Mudroch 1979) and one in 1979 (Rathke 1984). The 1971 samples were the surface 3 cm while the 1979 samples used the surface 10 cm. Direct comparison is thus not possible. However, because the more contaminated sediments of 1971 were being buried by less contaminated sediments by the late seventies, the collection of a 3 cm sample in 1979 might well have revealed an even greater decrease in concentrations than are seen in the 10 cm samples. Toxic metal concentrations in the surface 3 cm of surficial sediments, shows that Pb, Cd and Hg concentrations in the lower Great Lakes are higher over greater areas of the lake bottom than for the three upper Great Lakes. In 1971 (Thomas 1981) large areas of the lake bottom had concentrations of Pb greater than 150 ppm whereas in 1979 only small areas had greater than 100 ppm (Rathke 1984). In the central basin, where concentrations in 1971 had been greater than 100 ppm, levels have declined to less than 75 ppm, presumably by burial, dilution, or dispersion downstream of the historically contaminated sediments or downstream transport. The 1971 survey revealed two Pb plumes, one from Detroit to the western basin and one from Cleveland to the Central basin (Thomas 1981). In 1970, Konasewich *et al.* (1978) reported levels of 340 and 420 ppm Pb for Cleveland and Buffalo harbours respectively. The same effect is seen for Cd (Figure 9). Background (pre-colonial) bottom sediment concentrations of Cd in Lake Erie are 0.1 to 1.7 ppm. Surface sediment Cd concentrations in near shore areas were 0.1–8.3 ppm and in harbours 0.2–0.3 ppm (Fitchko and Hutchinson 1975; Mudroch *et al.* 1985). The lake bottom sediment average Cd concentration for western Lake Erie was reported as 6.6 ppm (Nriagu *et al.* 1979). The pattern for Hg in Lake Erie sediments is again similar. In 1971, a small area of the western basin of Lake Erie had bottom sediment concentrations of greater than 2 ppm Hg and a large area of over 1 ppm (Thomas and Jacquet 1976). By 1979, the anomaly was farther out into the west basin away from the inflow of the Detroit River and the area of greater than 1 ppm Hg had decreased considerably indicating a rapid recovery from earlier Hg contamination (Rathke 1984). Suspended solids entering Lake Erie from the Detroit River had shown little change in Hg concentration during 1974 (Thomas and Jacquet 1976) when the mean value was 1.06 ppm. In 1971, mean surficial sediment Hg concentrations in the west basin were 1.14 ±1.28 ppm compared to 0.60 ±0.42 ppm in 1979. The comparable values for Pb, Cd and As were 86 ±48 and 56 ±36 ppm; 5.6 ±3.5 and 3.0 ±2.4 ppm; and 7.9 ±2.5 and 6.5 ±3.0 ppm respectively.

Data on the concentrations of toxic organic chemicals in Lake Erie surficial sediment is given in Table 11. In 1971 the distribution of toxic organic chemicals in Lake Erie surficial sediments showed that the highest concentrations for hydrophobic compounds such as DDE and dieldrin were found in a plume originating from the Detroit River. In the top 3 cm bottom sediment samples from 1971, TDE was the predominant compound of the DDT group present. The mean TDE lake value was 18.4 ppb with a range of 0.3 to 186 ppb. Both TDE and DDE concentrations were 2 to 3 times higher in the depositional basins than in the other parts of the lake. The highest value of TDE was 46.5 ppb in the western basin. DDE was 22.1 ppb giving a total TDE and DDE value of 68.6 ppb. In 1980 at a site in the western basin, DDE was 8 ppb, DDE was 2 ppb and DDT was 1 ppb (a total of 11 ppb) in the upper 3 cm of sediment (Anderson 1980). Oliver and Bourbonniere (1985) reported that p,p'-DDD were evenly distributed across Lake Erie. The sum of dichloro through hexachlorobenzenes in Lake Erie sediment was some 26 ppb, less

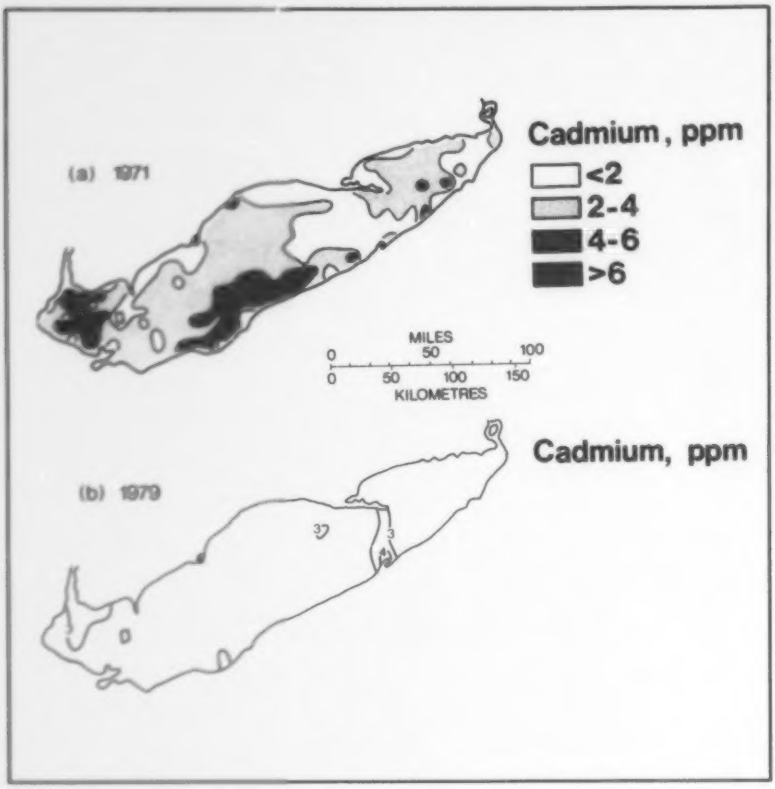

Figure 9. Cd in surficial bottom sediments of Lake Erie (a) 1971 (after Thomas and Mudroch 1979) and (b) 1979 (after Rathke 1984).

than in both Lake Huron (38 ppb) and Lake Ontario sediment (560 ppb) (Oliver and Nicol 1982). In 1982, HCB in 3 cm samples from the western, central and eastern basins of Lake Erie had concentrations of 9.1 ppb (range 4.6–17 ppb); 2.4 ppb (range 1.2–3.7 ppb); and 2.7 ppb (range 1.4–5.2 ppb) respectively (Oliver and Bourbonniere 1985). In the same samples, they detected HCBD at concentrations of 1.6 ppb (0.7–3.2 ppb); 0.2 ppb (0.1–0.4 ppb); and 0.2 ppb (0.1–0.6 ppb) respectively, or an overall depositional basin mean of some 0.7 ppb. In 1982, total PAH's in the adjacent Raison River in western Lake Erie ranged from 530–770 ppb (Eadie *et al.* 1982). Extreme concentrations of 4.8 to 390 ppm PAH were found in the sediments of the Black River near steel industries. The distribution of PAHs in the three basins of Lake Erie (Nagy *et al.* 1989) showed that B(a)P had highest concentrations of some 200 ppb in the central basin. Surface sediment PCDD and PCDF concentrations for Lakes Erie, Ontario, Huron, and Michigan were determined by Czuczwa and Hites (1986). The main isomer present was OCDD followed by H7CDF. Lake Erie concentrations of OCDD were 1,700 and 2,000 ppt; compared to 4,800 ppt for Lake Ontario; 780 and 960 ppt for Lake Michigan; and 880 ppt for Lake Huron. OCDF concentrations were much lower than in Lake Ontario. The surficial lake bottom sediment data on PCBs is the most extensive for toxic organic chemicals (Table 11). The highest levels were in the western basin and associated with inputs from the Detroit River.

In cores collected in 1971, rapid increases occurred in Hg and Pb concentrations after 1935 and especially after 1955 for Hg. Based on these analyses, the sediment concentration of Hg in 1971 was some 12.4 times that in pre-colonial sediments (Kemp and Thomas 1976a). In surface sediments, Pb was 4.4 times and Cd was 3.6 times the precolonial concentrations. More recent data shows that this trend has been reversed. Distribution of Pb in a dated core from the eastern basin of Lake Erie showed that concentrations of this metal began to increase slowly from about 3 ppm at the turn of the century, increased in the 1940's, rose rapidly from around 30 ppm in 1950, peaked at 58 ppm in the early 1970's, and have since declined to values of 30 ppm similar to those of around 1955 (Eddie and Robbins 1987) (Figure 10). In cores collected in 1985, recent declines from 13 to 9 ppm in As concentrations in bottom sediment have also been recorded (Legault 1986). Peak As concentrations occured around 1955 and since then have declined to concentrations similar to those which were recorded around 1945. Lake Erie sediment cores analyses initiated that there has been a recent recovery from earlier previous contamination by toxic organic chemicals. In 1971, p,p'-DDE was found to a depth of 10–12 cm or to around 1958–60 (Figure 10) (Frank *et al.* 1977). TDE in the same core was first detected at a depth of 6–8 cm, representing 1961–1963. DDE and TDE then increased rapidly to surface concentrations of 19 and 53 ppb respectively. Ten years later, Anderson (1980) reported that the upper 3 cm of sediment in a core from the eastern basin had DDT, DDE and DDD concentrations of 1 ppb, 2 ppb and 8 ppb respectively. The highest concentrations of total DDTs was 23 ppb at a depth of 15 cm. Beneath this depth, concentrations fell to 15 ppb total DDTs at 35 cm depth. For dioxins and furans, the high sedimentation rates of Lake Erie allow good resolution of historical input trends. In two cores, the maximum input of PCDD and PCDF was in the mid-1970s (Czuczwa and Hites 1986). Following the mid-1970s, inputs declined (Figure 10). Extrapolation to deeper layers and times of sediment

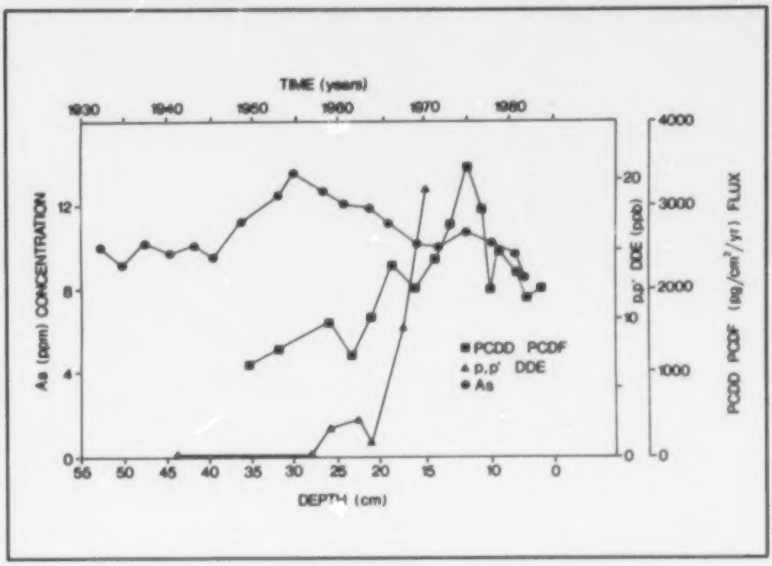

Figure 10. Distribution of As, DDE and PCDD + PCDF in Lake Erie sediment cores. (After Czuczwa and Hites 1986a; Legault 1986; Frank *et al.* 1977.)

deposition indicated that initial inputs of PCDDs and PCDFs to Lake Erie probably occurred in the mid to late 1930's.

In 1971, in a core from near Toledo, PCBs were in sediment deposited during 1954–1956. The upper layers had progressively rapidly increasing PCB concentrations of up to 340 ppb for the layers being deposited in 1971 (Frank *et al.* 1977). In 1982, the surface 3 cm of sediment for the western, central and eastern basins of Lake Erie had PCB concentrations of 300 ppb (range of 140–660 ppb); 131 ppb (range 38–190 ppb); and 91 ppb (range 37–140 ppb) (Oliver and Bourbonniere 1982). These values can be compared with the mean western basin, surficial 3 cm of sediment concentration of 252 ppb in 1971 (Frank *et al.* 1977). The reasons may be that the surficial sediments of the western basin are thoroughly mixed as proposed by Eadie and Robbins (1987) or the inputs of PCB's have not significantly declined.

The Niagara River

The Niagara River connects Lake Erie to Lake Ontario. It is a short connecting channel of about 60 km length with a very large discharge. The river is divided into upper and lower reaches by Niagara Falls. The main sources of pollution to the river were point source discharges from steel and petrochemical industries and municipal wastewater treatment plants (Figure 11). These treatment plants often received discharged effluents from industries. The large petrochemical industries on the United States side of the river have produced a variety of chlorinated industrial organic chemicals and pesticides. Most of the wastes from these petrochemical industries have been buried in waste landfills such as Hyde Park and Love Canal. These sites now produce leachates which enter the Niagara River.

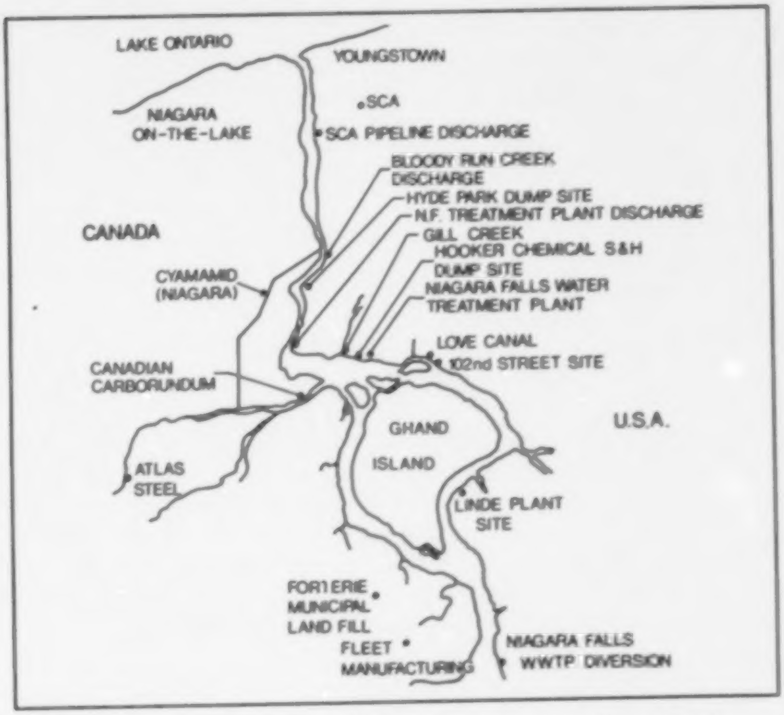
LAKE ONTARIO
YOUNGSTOWN
SCA
NIAGARA ON-THE-LAKE
SCA PIPELINE DISCHARGE
BLOODY RUN CREEK DISCHARGE
HYDE PARK DUMP SITE
N.F. TREATMENT PLANT DISCHARGE
GILL CREEK
HOOKER CHEMICAL S&H DUMP SITE
NIAGARA FALLS WATER TREATMENT PLANT
CANADA
CYAMAMID (NIAGARA)
LOVE CANAL
102nd STREET SITE
CANADIAN CARBORUNDUM
GHAND ISLAND
U.S.A.
ATLAS STEEL
LINDE PLANT SITE
FOR1 ERIE MUNICIPAL LAND FILL
FLEET MANUFACTURING
NIAGARA FALLS WWTP DIVERSION

Figure 11. Major effluent outfalls and waste dumps adjacent to the Niagara River (Allan *et al.* 1983).

Research results on the Niagara River and downstream Lake Ontario were published in a special volume of the Journal of Great Lakes Research (Allan *et al.* 1983). Numerous research and monitoring papers and reports have also been since published on the Niagara River pollution status. The Niagara River was the subject of a major bi-national study Niagara River Toxics Committee Study (NRTC 1984) which has described the pollution of the river in far more detail than can be described here. The NRTC (1984) reported, amongst other conclusions, that 261 man-made chemicals were identified in the ecosystem; 1400 kg of pollutants were discharged to the river from municipal and industrial point sources; 89% of the total came from U.S. sources; 61 U.S. hazardous waste disposal sites and 5 Canadian landfills have the potential to contaminate the river (and downstream); 28 of these 61 sites have or are contributing contaminants to the river; and general groundwater contamination covers a large area along the U.S. side of the river. Since release of the this, Canada and the United States have agreed to a plan which has a goal of 50% reduction of selected persistent toxic chemicals from both point and non-point sources by 1996.

In general, the longer term monitoring data on suspended solids on the Niagara River and the more recent water analyses comprise the best long term (1979 for metals) (1980 for organics) water quality data for toxic chemicals available anywhere in the Great Lakes. The data indicate an overall decline in concentration of many contaminants. This decline is recorded downstream in the bottom sediments of Lake Ontario and will be discussed later.

Between 1981/2 and 1986/7, the point source loadings to the Canadian side were estimated to have decreased by 60% (MOE 1987). On the United States side, an 80% reduction in total organic and inorganic priority pollutants from point sources was estimated to have taken place between 1981/82 and 1985/86 (NYDEC 1987). A significant fraction was related to plant closings or process shutdowns (NYDEC 1987). In 1984, no assessment could be made of the loadings of toxic chemicals via groundwater from 215 hazardous waste sites (NRTC 1984). Further study concluded that 61 of the 164 sites within 5 km of the river have the potential to contaminate it (NRTC 1984). Of the 17 landfill sites on the Canadian side, 5 were identified with a potential to contaminate the Niagara River (Koszalka *et al.* 1985). Although estimates of inputs have been made, they are extremely tenuous and considerably greater sampling and modelling will be needed to arrive at meaningful loadings. The existing estimates are based on 70 sites on the U.S. side of the river and arrive at a total of 180 kg/day of organic compounds. Thus, there is a possibility that non-point groundwater sources of chemicals could be as high as point source inputs to the Niagara River. The four major superfund sites of 102nd Street, Love Canal, S-area and Hyde Park collectively hold 304,000 tonnes of chemical waste; are hydraulically connected to the river; and have been associated with off-site migration of chemicals (Brooksbank 1987). Several of the small tributaries to the Niagara River contain bottom sediments with elevated concentrations of toxic contaminants and these could be a longer term source of pollutants to the river.

The Niagara River has been the most intensely studied part of the Great Lakes system for toxic metals and organic chemicals. This has occurred because the Niagara River was the first major area (1980) of crisis due to toxic organic chemical contamination, following closely on the exposure of Love Canal as a major chemical waste site. Monitoring for toxic metals using suspended solids went into effect in Canada in the late 1970's. By the early 1980s, this method had been extended to toxic organic chemicals in suspended solids at the mouth of the Niagara River. Later, in the mid-1980s, more sophisticated aqueous phase analyses were performed. All of these developments required new sampling and analytical techniques which have since been extended both up and downstream in the Great Lakes system.

By 1984, both upstream (Fort Erie) and downstream (Niagara-on-the-Lake (NOTL) monitoring had been implemented to calculate mass balances of specific toxic chemicals in the river by Federal agencies in Canada. Meanwhile, several special studies of chemical distribution in and sources to the river have been carried out by both Federal and Provincial (Ontario) Canadian agencies. A summary of the differential concentrations between Fort Erie and NOTL (Table 13) is based on values agreed to by the Canadian and U.S agencies responsible for the program. There has, of course, been considerable debate about sampling, analytical and data reduction techniques to arrive at these estimates. Loadings of 25 chemicals or elements were considered to be significantly higher at the NOTL location, either in the water or suspended sediment fractions or both in 1984/86 and 1986/87. Regardless of the exact numbers for specific compounds, even if these are accurate, it is clear that large amounts of chemicals have been or are still being introduced to the Niagara River along its shores.

Between 1984 and 1987, Environment Canada collected data on water and suspended solids concentrations at NOTL and Fort Erie. Two reports have been released, the first for Dec. 1984 to March 1986 and the second for April 1986 to March 1987. Collectively, the data in these reports on organic chemicals concentrations in the water and suspended solids at NOTL and Fort Erie represent the most comprehensive data base of its type anywhere in the world. Suspended solids are sampled by high speed centrifugation. Concentrations in the aqueous fraction are based on a continuous extraction system over a 24 hour period. The objective has been to assess the differential loads of toxic organic chemicals added along the course of the Niagara River. Of more importance in this report are the mean and range of concentrations recorded at both sites. A value for recombined water (RWW) was calculated from the aqueous concentration combined with the suspended solids concentrations based on the suspended solids content of the water. Using these values for RWW, 21 of the organic chemicals exceeded the strictest water quality criteria at least once, 15 at both NOTL and Fort Erie, 3 at Fort Erie only, and 3 at NOTL only. This data base reveals the extremely low concentrations of those chemicals present in the raw waters of connecting channels and Great Lakes.

Chemical Concentrations in Water and Suspended Solids: Between 1975 and 1979 less than 10% of the samples analysed at the mouth of the Niagara River exceeded the 1978 Water Quality Agreement (GLWQA) objectives, yet the river was a source of toxic metals and organic chemicals to Lake Ontario (DOE and MOE 1981). The main compounds of concern were DDT, PCBs, Mirex and Hg. Most organic chemicals were beneath the detection limits for water, which in turn are usually beneath the GLWQA objectives. In 1980, PCBs, α-BHC and lindane; and α and γ-chlordane, HCB, dieldrin, heptachlor epoxide, and p,p'-DDE were observed in 80% of ambient waters collected over a 10 day period at the mouth of the Niagara River (Kuntz 1983).

Partitioning of organic chemicals between aqueous and particulate fractions varies considerably with respect to location in the river and with time. The majority of the toxic organic chemical load in this river with a low (5 to 10 mg/L) suspended solids concentration, is in the aqueous phase. Collection and analyses of suspended solids at the mouth of the Niagara has been of great importance in establishing long term concentration trends. However, Kuntz and Warry (1983) found that only 40% of the total loadings to Lake Ontario of p,p'-DDE, Mirex and PCB's, all extremely hydrophobic organic chemicals, were in the particulate phase. The percentage was significantly less for most other toxic organics.

The general pattern of toxic chemical concentrations, at least in the Niagara River above Niagara Falls, results primarily from sources along the United States side of the River (IJC 1987b). The presence of compounds such as dioxins and furans which were never produced commercially but are known to be present in chemical waste disposal sites implies active leaching from these to the Niagara River. This conclusion was arrived at by both the NRTC (1984) and from results showing that specific compounds associated only with specific waste disposal sites are widespread downstream in Lake Ontario sediments (Kaminsky, *et al.* 1983).

Between 1984 and 1987, Environment Canada collected whole water samples for metal analyses from NOTL and Fort Erie. The mean concentrations and ranges are given for Pb, Cd, and As in Table 13. In 1981, the highest levels of Pb in water were 2, 3, and 5 ppb (Kuntz 1984b). These were found just downstream of Buffalo. Between 1975 and 1983, the 12-month moving average of total lead concentrations seems to show a decrease and translates into loading reductions of from some 430 tonnes/annum in 1975 down to some 200 tonnes/annum in 1983 (Kuntz 1988b). Between 1979 and 1980, Kauss (1983) reported that mean Hg concentration in the Tonawanda Channel were 100 ppt as opposed to 60 ppt in the Chippawa Channel. Mercury concentrations (MOE and DOE 1981) were from 60 to 110 ppt in waters of the upper Niagara River. In 1986, Hg was beneath the detection limit at NOTL and at FE. In 1982 to 1983, the analytical detection limit for Cd was 10 ppb which is above the GLWQA objective of 2 ppb (Kuntz 1984a). In 1985, the Cd concentrations at both NOTL and Fort Erie were beneath the detection limit of 2 ppb at 1.5 m depths. During 1980, As concentrations in the upper Niagara River were 1 or less than 1 ppb, the detection limit.

Because of the major focus on the Niagara River as a source of toxic organic chemicals to Lake Ontario, the organic chemical data base on waters is more extensive than elsewhere. Concentrations of toxic organic chemicals in the Niagara River are found in Table 12. For total DDT plus metabolites; endrin; heptachlor/heptachlor epoxide; and endosulphan, the 1978 GLWQA objectives have been exceeded occasionally in less than 10 % of the water samples (DOE and MOE 1981). Most concentrations were less than 1 or 5 ppt depending on the detection limit of the compound. Most PCB concentrations were less than the detection limit of 20 ppt. In 1979, the highest values recorded were 80 ppt total PCB's; 20 ppt dieldrin, 7 ppt α-BHC; 1 ppt lindane; 5 ppt total DDT and metabolites; and 15 ppt HCB (MOE and DOE 1980). Most of these elevated concentrations were from the U.S. side of the upper Niagara River.

Kuntz (1984b) found that concentrations of total DDT were 1–2 times greater at NOTL than at Fort Erie between 1975 to 1982. El-Shaarawi *et al.* (1985) said there was a significant difference in mean concentrations between Fort Erie and at NOTL for sixteen toxic chemicals. For whole water, some of these were PCBs, α-BHC, Mirex, and some CBs including HCB. Lindane and p,p'-DDE in the aqueous phase and Hg in the suspended phase also increased. McCrea *et al.* (1985) found the α-BHC, lindane and dieldrin, and to a lesser extent p,p'-TDE were mainly in the aqueous phases.

Chemical	Sample	Place	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	whole	UNR	1979	168			1,000				23	(4)
Pb	whole	NOTL	1976–83	394					<1,000-2,000			(2)
Pb	whole	FE	1985				1,000	1,000				(7)
Pb	whole	NOTL	1985				1,000	1,000				(7)
Pb	whole		<1986				1,000					(5)
Pb	whole	FE	1986–87	48	800	2,100	1,400				29	(1)
Pb	whole	NOTL	1986–87	45	900	2,600	1,600				27	(1)
Hg	whole	UNR	1979	144			10				85	(4)
Hg	whole	NOTL	1979–82	202					<50			(2)
Hg	whole	NOTL	1983	50					<20			(2)
Hg	whole	FE	1985				<20					(7)
Hg	whole	NOTL	1935				<20					(7)
Hg	whole		<1986				70					(5)
Cd	whole	UNR	1979	165			<1,000				98	(4)
Cd	whole	NOTL	1976–83	394					<1,000			(2)
Cd	whole	FE	1985				<1,000					(7)
Cd	whole	NOTL	1985				<1,000					(7)
Cd	whole		<1986				100					(5)
Cd	whole	FE	1986–87	48	90	120	100				58	(1)
Cd	whole	NOTL	1986–87	45	100	170	130				56	(1)
As	whole	UNR	1979	94			4,000				0	(4)
As	whole	NOTL	1980–83	211					500-1,100			(2)
As	whole	FE	1985				500	200				(7)
As	whole	NOTL	1985				700	400				(7)
As	whole		<1986				500					(5)
As	whole	FE	1986–87	49	590	640	610				0	(1)
As	whole	NOTL	1986–87	48	690	840	760				0	(1)
tDDT	whole		<1986				0.4					(5)
p,p'-DDT	whole	UNR	1979	72			<1			1	99	(4)
p,p'-DDT	whole	NOTL	1980–82	75			0.2	0.5	<0.1		60	(4)
p,p'-DDT	dis.	FE	1981				0.015					(4)
p,p'-DDT	dis.	NOTL	1981				0.02					(4)
p,p'-DDT	dis.		1981		0.01	0.05						(10)
p,p'-DDT	whole	NOTL	1985–86	43	1.2	20.1	11.2	7.7				(8)
p,p'-DDT	part.	FE	1986–87	45	0.14	0.21	0.17	0.74			20	(1)
p,p'-DDT	part.	NOTL	1986–87	42	0.026	0.05	0.036	0.64			86	(1)
p,p'-DDE	whole	UNR	1979	72			<1			1	94	(4)
p,p'-DDE	whole	NOTL	1980–82	75			0.3	0.5	0.1		39	(4)
p,p'-DDE	dis.	FE	1981				ND					(4)
p,p'-DDE	dis.	NOTL	1981				0.015					(4)
p,p'-DDE	whole	NOTL	1981	5		ND				0.5	100	(9)
p,p'-DDE	whole	NOTL	1985–86	43	0.1	33.5	2.9	8.5				(8)
p,p'-DDE	part.	FE	1986–87	45	0.32	0.48	0.39	0.75			0	(1)
p,p'-DDE	part.	NOTL	1986–87	42	0.044	0.052	0.048	0.31			45	(1)
dieldrin	whole	UNR	1979	72			<1			1	68	(4)
dieldrin	whole	NOTL	1980–82	75			0.6	0.3	0.6		7	(4)
dieldrin	dis.	FE	1981				0.26					(4)
dieldrin	dis.	NOTL	1981				0.27					(4)
dieldrin	dis.		1981		0.2	0.35						(10)
dieldrin	whole	NOTL	1981	5	ND	0.9				0.5	60	(9)
dieldrin	whole	NOTL	1985–86	43	0.3	8.2	2.9	4.6				(8)
dieldrin	whole		<1986				0.6					(5)
dieldrin	dis.	FE	1986–87	44	0.3	0.34	0.32	0.3			4	(1)
dieldrin	dis.	NOTL	1986–87	38	0.28	0.34	0.31	0.36			16	(1)

Table 12. *(Continued on following page)*

Chemical	Sample	Place	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
dieldrin	part.	FE	1986–87	45	0.013	0.029	0.02	1.2			82	(1)
dieldrin	part.	NOTL	1986–87	42	0.015	0.023	0.019	0.46			81	(1)
α-BHC	whole	UNR	1979	72			7			1	0	(4)
α-BHC	whole	NOTL	1980–82	75			10.5	5.2	9.7		0	(4)
α-BHC	dis.	FE	1981				2.89					(4)
α-BHC	dis.	NOTL	1981				5.5					(4)
α-BHC	dis.		1981		<1	8						(10)
α-BHC	whole		1981	5	ND	7				0.5	20	(9)
α-BHC	whole	LO	1982	244	1	84						(11)
α-BHC	whole	NOTL	1985–86	43	0.5	3.6	1.7	1.1				(8)
α-BHC	whole		<1986				10					(5)
α-BHC	dis.	FE	1986–87	44	2.71	2.33	2.51	0.3			2	(1)
α-BHC	dis.	NOTL	1986–87	38	2.24	2.65	2.44	0.31			3	(1)
α-BHC	part.	NOTL	1986–87	42	0.0096	0.043	0.022	1.65			76	(1)
lindane	whole	UNR	1979	72			1			1	16	(4)
lindane	whole	NOTL	1980–82	75			2.1	1.5	1.8		1	(4)
lindane	dis.	FE	1981				0.59					(4)
lindane	dis.	NOTL	1981				1.5					(4)
lindane	dis.		1981		0.5	1.8						(10)
lindane	whole		1981	5	ND	0.9				0.5	40	(9)
lindane	whole	LO	1982	245	<1	28					3	(11)
lindane	whole		<1986				2					(5)
lindane	dis.	FE	1986–87	44	0.6	0.68	0.64	0.25			4	(1)
lindane	dis.	NOTL	1986–87	38	0.6	0.7	0.65	0.28			8	(1)
Mirex	whole	NOTL	1980–82	75			<0.1		<0.1		99	(4)
Mirex	whole		<1986				0.3					(5)
Mirex	part.	NOTL	1986–87	42	0.016	0.03	0.022	0.74			83	(1)
toxaphene	whole		<1986				0.6					(5)
B(a)P	whole		<1986				0.3					(5)
B(a)P	part.	NOTL	1986–87	42	1.05	2.28	1.59	0.63			88	(1)
TeCB	dis.	NOTL	1986–87	38	0.56	0.92	0.72	0.82			11	(1)
TeCB	part.	NOTL	1986–87	42	0.19	0.45	0.3	1.29			7	(1)
HCB	whole	UNR	1979	72			<1			1	97	(4)
HCB	whole	NOTL	1980–82	75			0.8	0.9	0.5		5	(4)
HCB	whole	NOTL	1981	5		ND				0.5	100	(9)
HCB	whole	LO	1982	245	<1	8					88	(11)
HCB	whole	NOTL	1985–86	43	0.1	4.3	1.5	1.5				(8)
HCB	whole		<1986				0.4					(5)
HCB	dis.	NOTL	1986–87	38	0.11	0.13	0.12	0.36			8	(1)
HCB	part.	NOTL	1986–87	42	0.11	0.23	0.17	1.11			28	(1)
HCBD	whole	NOTL	1985–86	43	0.1	0.2	0.2	0.1				(8)
HCBD	dis.	NOTL	1986–87	38	0.09	0.12	0.11	0.45			29	(1)
HCBD	part.	NOTL	1986–87	42	0.035	0.11	0.066	1.45			60	(1)
PCBs	whole	UNR	1979	72			5			20	81	(4)
PCBs	whole	NOTL	1980–82	75			19.9	34.7	11		3	(4)
PCBs	dis.	FE	1981				0.26					(4)
PCBs	dis.	NOTL	1981				0.8					(4)
PCBs	dis.		1981		0.2	1.3						(10)
PCBs	whole	NOTL	1981	5	ND	39				5	60	(9)
PCBs	whole		<1986				10					(5)
PCBs	dis.	FE	1986–87	44	2.57	3.26	2.9	0.09			93	(1)
PCBs	part.	FE	1986–87	45	0.88	1.14	1.0	0.49			36	(1)
PCBs	part.	NOTL	1986–87	42	1.42	1.91	1.66	0.54			2	(1)

Table 12. *(Continued on following page)*

Chemical	Sample	Place	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
TCDD	dis.		1984	6		ND					100	(3)
TCDD	part.		1984	8		ND					100	(3)
PnCDD	dis.		1984	6	ND	0.3					83	(3)
PnCDD	part.		1984	8	ND	76					75	(3)
HxCDD	dis.		1984	6	ND	0.4					67	(3)
HxCDD	part.		1984	8	ND	177					38	(3)
HpCDD	dis.		1984	6	ND	1.4					83	(3)
HpCDD	part.		1984	8	ND	238					38	(3)
OCDD	dis.		1984	6	ND	3.6					17	(3)
OCDD	part.		1984	8	ND	228					12	(3)
TCDF	dis.		1984	6	ND	156					83	(3)
TCDF	part.		1984	8	ND	412					50	(3)
PnCDF	dis.		1984	6	ND	317					33	(3)
PnCDF	part.		1984	8	ND	300					12	(3)
HxCDF	dis.		1984	6	ND	14					67	(3)
HxCDF	part.		1984	8	ND	495					25	(3)
HpCDF	dis.		1984	6	ND	1.5					83	(3)
HpCDF	part.		1984	8	ND	2,450					25	(3)
OCDF	dis.		1984	6	ND	0.5					33	(3)
OCDF	part.		1984	8	2.2	2,530					0	(3)

ND : not detected
Sample : whole = whole water; dis. = aqueous phase; part. = suspended particulate phase.
Place : testing place
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit
FE : Fort Erie
NOTL : Niagara-on-the-Lake
LNR : Lower Niagara River, north of Niagara Falls.
UNR : Upper Niagara River, south of Niagara Falls
LO : Samples taken from the Niagara River plume in Lake Ontario.

1. DOE, USEPA, MOE & NYDEC 1988. Minimum and maximum values represent 90% confidence intervals. Particulate concentration: Equivalent water concentration for particulate phase calculated as product of mean contaminant concentration on particulate and mean suspended sediment concentrations.
   Particulate conc. + dissolved concentration = whole water concentration.
   ND: not detected or not analysed for.
2. Kuntz 1988b. Weekly samples.
3. Hallett and Brooksbank 1986
4. Kuntz 1984b. Weekly sampling.
5. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
6. DOE and MOE 1981.
7. Kuntz and Biberhofer 1986
8. Maguire and Tkacz 1988
9. Maguire *et al.* 1983. Samples taken at 5 stations along the river in July, 1981.
10. McCrea *et al.* 1985. Concentrations listed here are approximations.
11. Fox and Carey 1985. Samples from the Niagara River plume in Lake Ontario.
12. Warry and Chan 1981a

Table 12. Toxic chemical concentrations in Niagara River water (ppt).

Over a two year period for 1981 to 1983, weekly water samples from Niagara-on-the-Lake were analyzed by Oliver and Nicol (1984) for several organic compounds and isomers. The distribution of the concentrations of α-BHC; total PCBs; 1,2,3,4-TeCB; and HCB show that maximum concentrations occurred as short-lived (one sample)

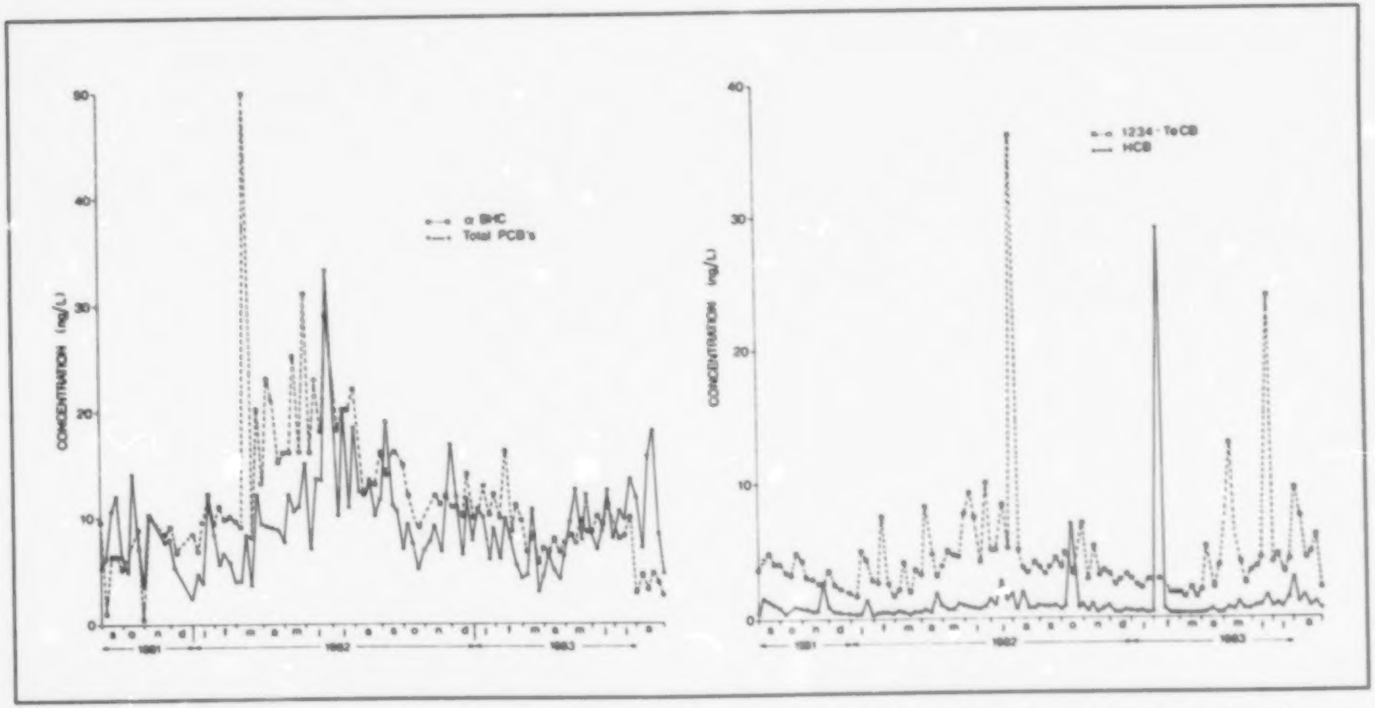

Figure 12. Concentrations of organic chemicals in weekly water samples from NOTL over a 2 year period, 1981–1983 (Oliver and Nicol 1984).

peaks (Figure 12). The peak concentrations were as follows: 50 ppt α-BHC; 34 ppt total PCBs; 36 ppt 1,2,3,4-TeCB; and 30 ppt HCB but on these occurred only on rare occasions. Normally, the concentrations were far less and for α-BHC and total PCBs were even and more seasonably varied than for HCB and 1,2,3,4-TeCB. Oliver and Nicol (1984) attributed this to the influence of non-point sources rather than point sources. This problem of short term fluctuations in chemical concentrations in the Niagara River has recently been resolved by installation of a continuous extraction system rather than by extraction of distinct samples taken at relatively short time intervals. Oliver and Nicol (1982) found that HCB concentrations in the water above Niagara Falls were near or below their detection limit of 0.02 ppt. They found higher concentrations of 1 ppt and 17 ppt near a chemical outfall and a waste disposal site respectively. In 1982, CBs, α-BHC and lindane were analysed for and detected in the Niagara River plume in Lake Ontario (Fox and Carey 1985). In 1979–80, Kauss (1983) found higher concentrations of α-BHC and lindane in the Tonawanda Channel than in the rest of the river. In 1986, Stevens and Neilson (in press) found dramatic increasing in CBs, with the exception of HCB between the outlet of Lake Erie and the Niagara River plume.

Between 1975 and 1982, Mirex was observed in the aqueous fraction of only 6 of 22 samples at levels of 0.0005–0.0075 ppt (Kuntz 1984b). El-Shaarawi *et al.* (1985) stated that between 1978 and 1984, there was a significant difference between concentrations of Mirex in the combined suspended sediment and aqueous phases at NOTL and Fort Erie. Waste dumps in the United States could contain large amounts of dioxins produced as by-products of chemical manufacturing (Hallett 1985). In 200 litre samples taken in tandem 6 m offshore, upstream, opposite and downstream of the 'S' area landfill (Figure 11), isomers of penta, hexa, hepta, and octachlorodioxins and dibenzofurans, including isomers of 2,3,7,8,9 pentachlorodioxin and dibenzofuran were detectable at concentrations in the order of 0.01 ppt (Hallett 1985). Residues of 2,3,7,8-TCDD and 2,4,5-trichlorophenol were not detected.

In the late 1970's, suspended solids collected at the mouth of the Niagara River were analyzed to determine trends in loads of toxic metals to Lake Ontario. In the 1980s, these particulates were analysed for toxic organic chemicals as well. A summary of the chemical concentrations in suspended sediments is given in Tables 12 and 13.

In 1981, a comparison of chemical analyses of suspended sediments from NOTL and from Thunder Bay in Lake Erie revealed that many of the chemicals detected at NOTL were not detectable

Chemical	Sample	Place	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	part.*	NOTL	1978	13			60,000	26,600				(3)
Pb	part.*	NOTL	1979-80	35			56,000	16,900				(3)
Pb	part.*	NOTL	1981	29			83,000	61,000				(1)
Pb	part.*	NOTL	1982	27			93,000	57,000				(1)
Hg	part.*	FE	1981				63					(1)
Hg	part.*	NOTL	1981				333					(1)
Cd	part.*	NOTL	1978	13			2,400	800				(3)
Cd	part.*	NOTL	1979-80	35			2,400	1,300				(3)
Cd	part.*	NOTL	1981	14			7,300	4,000				(1)
Cd	part.*	NOTL	1982	27			4,700	5,200				(1)
As	part.*	FE	1981				9,900					(1)
As	part.*	NOTL	1981				12,100					(1)
tDDT	part.*	NOTL	1979-80	41			30.4	16.3			0	(2)
p,p'-DDT	part.*	NOTL	1979-81	70			11	12	6		14	(1)
p,p'-DDT	part.*	NOTL	1979-80	41			10	10			20	(2)
p,p'-DDT	part.*	FE	1981				1					(1)
p,p'-DDT	part.*	NOTL	1981				25					(1)
p,p'-DDE	part.*	NOTL	1979-81	70			23	23	16		6	(1)
p,p'-DDE	part.*	NOTL	1979-80	41			24	12			7	(2)
p,p'-DDE	part.*	FE	1981				21					(1)
p,p'-DDE	part.*	NOTL	1981				9					(1)
dieldrin	part.*	NOTL	1979-81	70			4	3	4		20	(1)
dieldrin	part.*	NOTL	1979-80	41			5	3			38	(2)
dieldrin	part.*	FE	1981				9					(1)
dieldrin	part.*	NOTL	1981				6					(1)
α-BHC	part.*	NOTL	1979-81	70			12	23	4		25	(1)
α-BHC	part.*	FE	1981				9					(1)
α-BHC	part.*	NOTL	1981				12					(1)
lindane	part.*	NOTL	1979-81	70			2	4	<1		67	(1)
lindane	part.*	NOTL	1979-80	41			3.7	3.3			63	(2)
Mirex	part.*	NOTL	1979-81	70			12	32	5		24	(1)
Mirex	part.*	NOTL	1979-80	41			19.4	49.5			34	(2)
Mirex	part.*	FE	1981				ND					(1)
Mirex	part.*	NOTL	1981				1					(1)
B(a)P	part.*	NOTL	?1980		190	20,000						(1)
HCB	part.*	NOTL	1979-81	70			124	320	40		0	(1)
HCB	part.*	FE	1981				1					(1)
HCB	part.*	NOTL	1981				73					(1)
PCBs	part.*	NOTL	1979-81	70			716	597	500		0	(1)
PCBs	part.*	NOTL	1979-80	41			981	2,196			0	(2)
PCBs	part.*	FE	1981				ND					(1)
PCBs	part.*	NOTL	1981				367					(1)

ND : not detected
Sample : whole = whole water; dis = aqueous phase; part. = suspended particulate phase
Place : testing place
: number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit
FE : Fort Erie
NOTL : Niagara-on-the-Lake
part.* : Particulate concentrations are in ng/g (ppb)

1. Kuntz 1984b. Based on weekly sampling
2. Warry and Chan 1981
3. DOE and MOE 1981

Table 13. Toxic chemical concentrations in Niagara River suspended sediments (ppb, ng/g).

at Thunder Bay (DOE and MOE 1980). However, the process of arriving at mean values and calculations of loads or differences remains a complex issue. Wind generated resuspension events in Lake Erie can alter the suspended load of the Niagara River by 100% which has major effects on the partitioning of chemicals between suspended solids and the aqueous phase. McCrea *et al.* (1985) noted that PCB concentrations and suspended solids were lower when the suspended solids concentrations were higher due to input of clean sediment from Lake Erie. Thus, the partitioning between aqueous and suspended solids phases varies greatly both with respect to organic compound and location (NRTC 1984).

In the late 1970s, Pb concentrations are somewhat higher in the upper river perhaps because the method of sampling was intended to detect sources (DOE and MOE 1981). Hg concentrations in suspended solids were consistently 3 to 4 times higher in the lower than upper Niagara Rivers (Kuntz 1984b). The distribution of Hg and As in the suspended solids in the river showed that the former increases downstream in concentration whereas As appears to be relatively evenly distributed (Kuntz 1984b). The highest concentrations in 1981 for Hg was 450 ppb (ng/g) and for As it was 15 ppm (mg/kg).

In 1981, the distributions of toxic organic chemicals in suspended solids showed two patterns (Figure 13) (Kuntz 1984b). The first represented by DDT and dieldrin was one of relatively constant concentrations throughout the river. The second, represented by PCBs, Mirex and HCB showed that concentrations in the lower river were considerably higher than in the upper river. The maximum suspended solids concentrations for total DDT, dieldrin, HCB, Mirex and total PCBs were some 60 ppb; 175 ppb; 3 ppb and 800 ppb respectively. There are considerable variations of course with location and time. In 1980, Oliver and Nicol (1982) detected CB congeners in suspended sediments at NOTL. The mean concentrations ($n = 28$) were as follows: 1,2-Di 148 ppb; 1,4-Di 180 ppb; 1,3-Di 95 ppb; 1,3,5,-Tri 20 ppb; 1,2,4-Tri 61 ppb; 1,2,3-Tri 19 ppb; 1,2,4,5-Tetra 28 ppb; 1,2,3,4-Tetra 71 ppb; Penta 58 ppb; Hexa 94 ppb. The source of the particulate associated Mirex 1979–80, was considered to be leakage or overflow from storage facilities downstream of Grand Island (Warry and Chan 1981). Both PCDD and PCDF are strongly associated with suspended solids. The higher chlorinated congeners predominated.

Toxic organic chemical concentrations in suspended solids collected at the mouth of the Niagara River do not reveal any distinct trends over the period of measurements (DOE and MOE 1981; Kuntz 1983). Lake Erie is not the major source of such chemicals as PCBs,

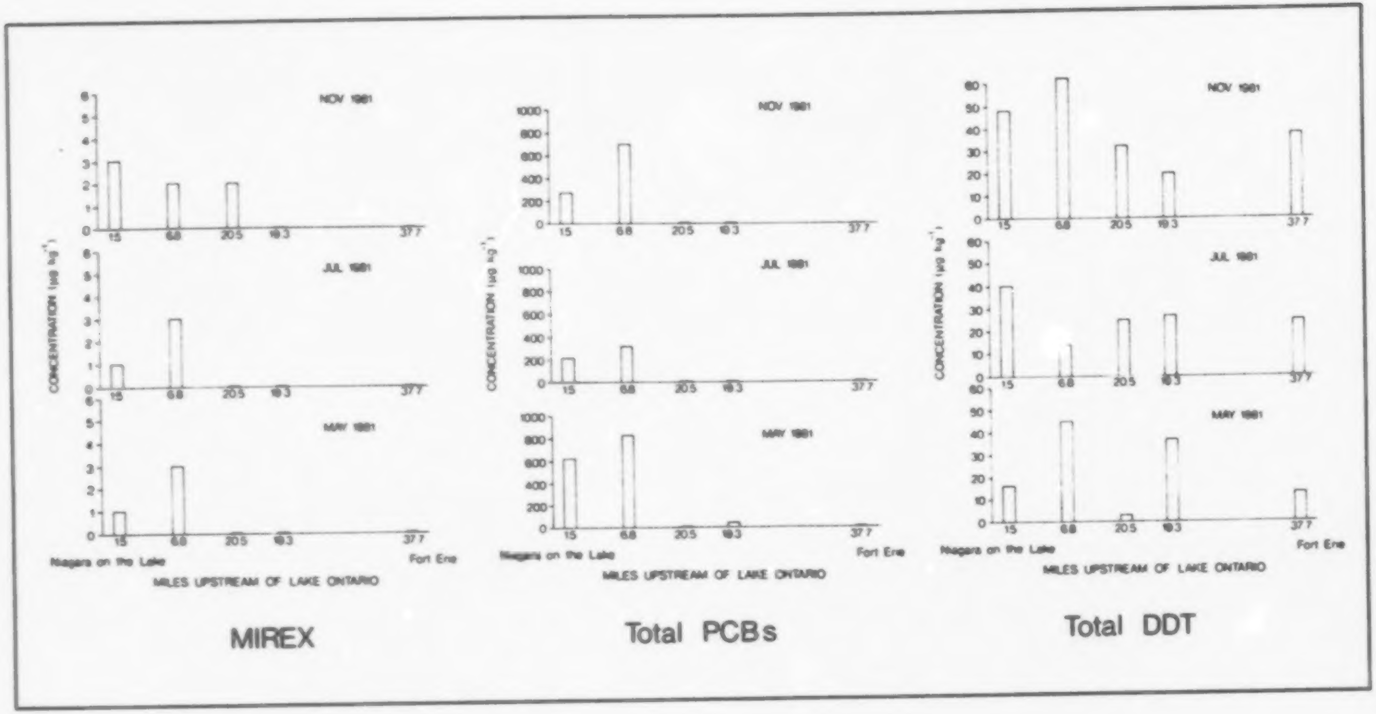

Figure 13. (Continued on following page)

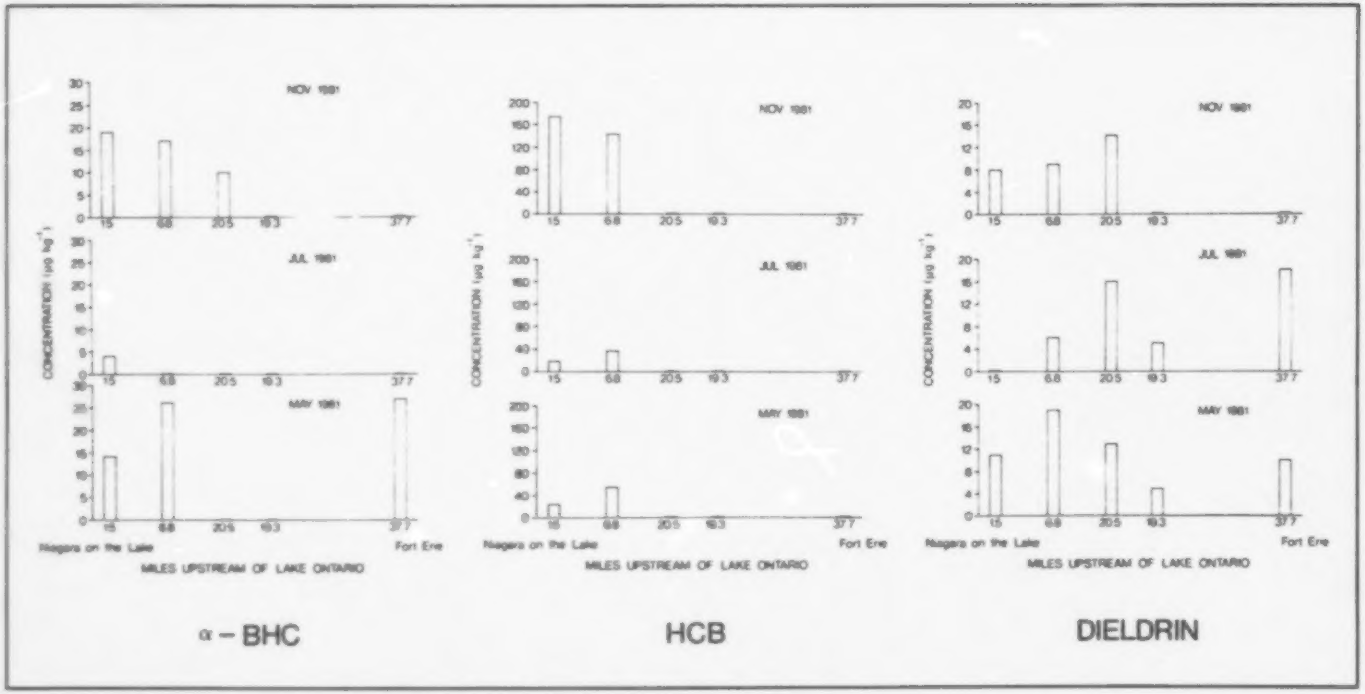

Figure 13. Distributions of total DDT; dieldrin; mirex; PCBs; α-BHC; HCB; and PCBs (all ppb) in suspended sediments in the Niagara River in 1981 (after Kuntz 1984b).

CBs and Mirex to Lake Ontario because concentrations of these chemicals in Lake Erie bottom sediments are ten times lower for PCBs, undetectable for Mirex and twenty times lower for CBs than the suspended solids concentrations at Niagara-on-the-Lake (Kuntz and Warry 1983). Similar conclusions were arrived at for these chemicals and for HCBD by Fox *et al.* (1983).

Chemical Concentrations in Bottom Sediments: The Niagara River has an extremely high discharge of about 6,000 m^3/sec. Above the falls there are some areas of nearshore sediment accumulation, at least on a temporary basis. The bottom of the river is either scoured glaciolacustrine sediments or bedrock with very little deposition of unconsolidated recent sediments (NRTC 1984). Most of the data which follows was based on sampling very nearshore or near the mouths of tributaries. The data is thus based on sediments from the Niagara River but is not a bottom sediment survey of the type discussed for the depositional basins of the open Great Lakes. The concentrations are more representative of relative sources on each side of the river. Some of these nearshore samples are highly contaminated by toxic metals and organic chemicals. Pesticides were generally most elevated in the Black Rock Canal, the Wheatfield-Upper River segment, but also in the Buffalo River and the Tonawanda-North Tonawanda and lower river segments (NRTC 1984). Dependent on the chemical, there is considerable variation in concentrations but the overall pattern is for higher pollutant levels in the Buffalo River, Tonawanda-North Tonawanda and Wheatfield-Upper River segments; medium levels in the Lake Erie, Black Rock Canal and Lower River segments; low levels in the Bird Island-Riverside, Fort Erie and Chippawa segments (NRTC 1984). Jaffe (1985) concluded that the Love Canal area was a major source of anthropogenic chemicals to the river and that the 102nd Street waste site was the major source of Mirex and BHC's. He also concluded that the distribution of fluorinated compounds in sediment cores from Lake Ontario, reflected the history of their disposal in the Hyde Park waste disposal sites. Inputs of these latter compounds have decreased since the mid-1970s and background levels for Lake Ontario surface sediments are predicted to be reached in the early 1990's (Jaffe 1985).

Concentrations of toxic chemicals in Niagara River bottom sediments are summarized in Table 14. In 1979, the highest concentrations of Pb, Hg and As were in bottom sediments from the Tonawanda Channel and the mouth of the Buffalo River (Kauss 1983). The bottom sediments violated the MOE open water dredge disposal guideline for Pb, Cd, Hg and As at many sites along the

Chemical	Sample	Place	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	UNR	1979	15	4,000	200,000			11,000		0	(2)
Pb	3 cm	LNR	1979	9	6,000	60,000			16,000		0	(2)
Pb	2.54 cm		1981	16	9,000	767,000	98,000	180,000				(1)
Hg	3 cm	UNR	1979	15	<10	670			90		7	(2)
Hg	3 cm	LNR	1979	9	30	3,200			340		0	(2)
Hg	2.54 cm		1981	16	20	2,450	607	754				(1)
Cd	3 cm	UNR	1979	15	<400	880			<400		60	(2)
Cd	3 cm	LNR	1979	9	<400	880			650		11	(2)
Cd	2.54 cm		1981	16	<100	19,000	2,200	4,400				(1)
As	3 cm	UNR	1979	15	1,900	14,000			3,300		0	(2)
As	3 cm	LNR	1979	9	1,500	8,200			3,500		0	(2)
As	2.54 cm		1981	16	3,000	20,000	7,800	5,100				(1)
tDDT	3 cm	UNR	1979	15	1	24			6		0	(2)
tDDT	3 cm	LNR	1979	8	4	190			10		0	(2)
p,p'-DDT	3 cm	UNR	1979	15		ND					100	(2)
p,p'-DDT	3 cm	LNR	1979	8	ND	74			ND		75	(2)
p,p'-DDT	2.54 cm		1981	16	<1	73			<1			(1)
p,p'-DDE	3 cm	UNR	1979	15	1	19			3		0	(2)
p,p'-DDE	3 cm	LNR	1979	8	4	36			9		0	(2)
p,p'-DDE	2.54 cm		1981	16	<1	280			2.5			(1)
dieldrin	3 cm	UNR	1979	15	ND	6			ND		67	(2)
dieldrin	3 cm	LNR	1979	7	ND	26			5		28	(2)
dieldrin	2.54 cm		1981	16	<1	10			<1			(1)
Mirex	3 cm	UNR	1979	15	ND	18			5		40	(2)
Mirex	3 cm	LNR	1979	8	ND	640			5		38	(2)
Mirex	2.54 cm		1981	16	<1	890			<1			(1)
α-BHC	3 cm	UNR	1979	15	ND	1			ND		93	(2)
α-BHC	3 cm	LNR	1979	8	ND	640					50	(2)
α-BHC	2.54 cm		1981	16	<1	2,260			2			(1)
lindane	3 cm	UNR	1979	14		ND					100	(2)
lindane	3 cm	LNR	1979	8	ND	20			ND		88	(2)
lindane	2.54 cm		1981	16	<1	87			<1			(1)
HCB	3 cm	UNR	1979	15	ND	22			ND		93	(2)
HCB	3 cm	LNR	1979	8	1	250			32		0	(2)
HCB	2.54 cm		1981	16	<1	110			2			(1)
PCBs	3 cm	UNR	1979	13	ND	960			220		8	(2)
PCBs	3 cm	LNR	1979	8	66	2,700			280		0	(2)
PCBs	2.54 cm		1981	16	<10	17,900			210			(1)

Tr: trace abundance
ND : not detected
Sample : depth of surficial sediment sample
Place : testing place
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit
LNR : Lower Niagara River, north of Niagara Falls.
UNR : Upper Niagara River, south of Niagara Falls

1. Kuntz 1984b.
2. DOE and MOE 1981.

Table 14. Toxic chemical concentrations in Niagara River bottom sediments (ppb).

United States side of the river from the Buffalo River to the Love Canal area (Kuntz 1984b). Breteler *et al.* (1984) reported that between 1940 and 1950, the mercury in Lake Erie sediments increased by no more than a factor of 2 whereas in the Niagara River delta the increases were from 10 to 20 fold. Sources were local and peak inputs to the delta were in 1950–54 followed by a leveling off after the older style rocking Hg electrodes were replaced in the chloralkali plants. After 1970, both Niagara Falls chloralkali plants began to reduce Hg concentrations in effluents. By 1971–72, they were down to a third of the peak in the early 1950's. By 1978 to 1979, the levels were about 12% of the 1969 to 1970 values and were approaching the levels representing the early 1940's (Breteler *et al.* 1984). In 1975 to 1981, high concentrations were found in the bottom sediments at nearly every station on the United States side between the Buffalo River and Love Canal. Values over 1 ppm Hg were observed in the Black Rock Canal and near Love Canal (Kuntz 1984b). The Cd and As concentration distributions were similar to those for Pb and Hg. Many high values of Cd, above the MOE open water dredge spoil guilelines of 1 ppm were found in the Black Rock Canal, the Buffalo River, near Love Canal and at one site in the lower river. In the late 1960s-early 1970s, the As concentrations in sediments from the Niagara Basin of Lake Ontario were 13 times higher than those from the Eastern Basin of Lake Erie (NRTC 1984). Levels of As in the Niagara River bottom sediments were generally below the MOE open water dredge disposal guideline of 8 ppm except in the Buffalo River and Black Rock Canal (Kuntz 1984b).

The distribution of toxic chemicals in the bottom sediments of the Niagara River were last determined systematically in 1981 (Kuntz 1984b). Parent DDT was found at 5 of 16 stations sampled. The highest DDT values were at the Black Rock Canal. Dieldrin was beneath the detection limit of 1 ppb at all but two sites. Mirex values were low throughout the entire river system except at one site near Love Canal where the concentration was 890 ppb. Based on bottom sediment analyses in 1981, Jaffe (1985) concluded that the 102nd Street waste site is a source of Mirex to the river. Kuntz (1984b) also reported on several other organic chemicals including methoxychlor, α and γ-chlordane, various CB congeners, other DDT metabolites and α and γ-endosulfan. No ambient water or sediment data has been reported for toxaphene in either the Niagara River or Lake Ontario (Strachan and Edwards 1984).

Lake Ontario

Lake Ontario, with a surface area of 19,000 km^2, is the 5th largest of the Great Lakes. Its volume of 1,640 km^3 ranks 4th in the Great Lakes and 11th in the world. With a maximum depth of 244 metres, it is the 3rd deepest of the Great Lakes. Retention time is about 8 years. By far the largest inflow of some 5,700 m^3/s is from the Niagara River. In decreasing order of discharge, other main tributaries are the Oswego, Trent, Black, and Genesee Rivers. The lake's discharge rate is approximately 7,700 m^3/s via the St. Lawrence River. Circulation in the southern section of Lake Ontario is to the east. The flow then turns north and travels west across the middle of the lake. South of Toronto, the current turns north and then east along the north shore. In the southwest, there is a counterclockwise circulation pattern. The Niagara River plume usually splits as it enters the lake with a smaller section joining the southwest counterclockwise circulation pattern and a larger section joining the easterly current along the south shore of the lake.

There has been extensive historical pollution of Lake Ontario from industrial, agricultural, and municipal sources. Industrialized harbours and embayments generally show the highest contaminant levels. Some of the main contaminants investigated in Lake Ontario are Hg, Mirex, PCBs, and CBs. Lake Ontario has the highest volume of Canadian urban runoff of persistent toxic substances (Marsalek and Schroeter 1984). The main industrial centres are Toronto, Hamilton, and Rochester and other important ports are Kingston and Oswego. Seven areas, four in Canada, plus the Niagara River, have been designated as Lake Ontario Areas of Concern by the International Joint Commission.

Chemical Concentrations in Water and Suspended Solids: Toxic metals concentrations in Lake Ontario water (Table 15) are less than in lakes Erie and Michigan and greater than lakes Huron and Superior (Rossmann and Barres 1988). Concentrations of Pb in the waters of Lake Ontario are low and uniform with a small zone of higher concentrations at the extreme west end of the lake (Schmidt and Andren 1984, Neilson 1983). Lake Ontario has significantly less total and dissolved Pb than Lake Erie and significantly less dissolved Pb than Lake Michigan (Rossmann and Barres 1988). Hg levels in Lake Ontario water are low (Table 15). Levels of total Hg in Lake Ontario were significantly less than those in Lakes Erie and Michigan while levels of dissolved mercury were significantly less than those of Lake Michigan (Rossmann and Barres 1988). In the late 1960s, Lake Ontario had the highest As concentrations of all the Great Lakes a maximum value of 1,200 ppt (Traversy *et al.* 1975) (Table 15). When dissolved and particulate As fractions are reported, the dissolved phase was at least 60% of the total concentration (Rossmann and Barres 1988).

DDT was banned in the early 1970s but still enters the lake via the atmosphere, from the regional use of dicofol which contains traces of DDT and metabolites, and as a photolytic product of methoxychlor which is still used in the Great Lakes basin (Biberhofer and Stevens 1987). In 1981, McCrea *et al.* (1985) found p,p'-DDT to be exclusively in the aqueous phase with an average concentration of just less than 0.04 ppt. In 1986, the mean concentration of p,p'-DDE in Lake Ontario (Table 15) was the same as in Lake Erie and about twice the concentration in Lake Huron.

In 1981, dieldrin concentrations of just less than 0.04 ppt in Lake Ontario were 100% in the aqueous phase (McCrea *et al.* 1985). In 1983, Biberhofer and Stevens (1987) reported that the highest levels of dieldrin were in the mid-lake area rather than at near-shore stations. The average concentration of dieldrin in 1986 was similar to that of Lakes Erie, Huron, and Superior and indicated that input is historical, atmospheric, or from resuspension of contaminated sediments (Stevens and Neilson 1989). In 1981, McCrea *et al.* (1985) found α-BHC and lindane completely in the aqueous phase at concentrations of 9 and 8 ppt respectively. In 1986, the mean concentration for α-BHC was similar to that of Lake Erie but lower than consentrations in Lakes Huron and Superior (Figure 14). Lindane concentrations were similar throughout the lakes (Stevens and Neilson 1989). The mean concentration of HCB in 1986, was lower than that of Lake Erie and higher than in lakes Huron and Superior (Stevens and Neilson 1989). Mirex is extremely insoluble and was not detected in the aqueous phase in 1977, 1981 and 1983 (Strachan and Edwards 1984; McCrea *et al.* 1985; Biberhofer and Stevens 1987) or in whole water samples in 1986 (Stevens and Neilson 1989). Mirex was detected in 1982 in water from Oswego Harbour (Mudambi *et al.* 1983) where concentrations in the dissolved phase, ranged from beneath the detection limit (0.005 ppt) to 0.130 ppt. Strachan and Eisenreich (1988) calculated whole water concentration of Mirex in Lake Ontario to be 0.060 ppt. The mean toxaphene concentration of 0.6 ppt in Lake Ontario was the same as the average for all the Great Lakes for that year (Sullivan and Armstrong 1985). Strachan and Edwards (1984) reported that there are no data for dioxins in the waters of Lake Ontario. Strachan and Eisenreich (1988) used a value of 3 ppt total water B(a)P concentration for their mass balance calculations. In 1981, the concentration of PCBs in the aqueous phase of Lake Ontario was 0.5 (McCrea *et al.* 1985). Ninety-one percent of the total PCBs was in the aqueous phase (McCrea

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	dis.	1985	22					ND		91	(5)
Pb	dis.	<1986				300					(11)
Pb	part.	1978	19	78	970						(2)
Pb	part.	1985	22					28		41	(5)
Pb	part.	<1986				100					(11)
Pb	whole	1979	532		3,000	310–400			500	67	(1)
Pb	whole	<1981		1,000	5,000						(12)
Pb	whole	1982	55			<500					(4)
Pb	whole	1985	22					40			(5)
Hg	dis.	1985	22					11		96	(5)
Hg	dis.	<1986				20					(11)
Hg	part.	1985	22					ND			(5)
Hg	part.	<1986				5					(11)
Hg	whole	1970–71	132	ND	300	130	70				(6)
Hg	whole	1979	528		160	25–27			50	98	(1)
Hg	whole	<1981				<200					
Hg	whole	1982	55			<10					(4)
Hg	whole	1985	22					10		73	(5)
Cd	dis.	1985	22					24		41	(5)
Cd	dis.	<1986				60					(11)
Cd	part.	1978	15	4.4	58						(2)
Cd	part.	1985	22					69		0	(5)
Cd	part.	<1986				60					(11)
Cd	whole	1979	532		300	50–60			100	92	(1)
Cd	whole	<1981		<1,000	15,000						(12)
Cd	whole	1982	55			<200					(4)
Cd	whole	1985	22					96			(5)
As	dis.	1985	22					490		9	(5)
As	part.	1985	22					24		86	(5)
As	whole	?1968	24	600	1,200	910			100	0	(3)
As	whole	1979	525		1,200	570–720			100	0.2	(1)
As	whole	1982	55			980					(4)
As	whole	1985	22					500			(5)
As	whole	<1986				500					(11)
tDDT	dis.	<1986				0.1					(11)
tDDT	part.	<1986				0.1					(11)
tDDT	whole	<1981		<10	60	35					(6)
tDDT	whole	1983	14	0.069	0.271	0.144	0.069	0.124			(10)
p,p'-DDT	whole	1986	31		ND				0.011	100	(8)
o,p'-DDT	whole	1986	31		ND				0.011	100	(8)
p,p'-DDE	whole	1986	31	0.023	0.139	0.053			0.011	6	(8)
dieldrin	dis.	<1986				0.3					(11)
dieldrin	part.	<1986				0.1					(11)
dieldrin	whole	<1981		1	10	4					(12)
dieldrin	whole	1983	14	0.259	0.631	0.405	0.14	0.48			(10)
dieldrin	whole	1986	31	0.075	0.514	0.331			0.011	0	(8)
α-BHC	dis.	<1986				6.0					(11)
α-BHC	part.	<1986				1.0					(11)
α-BHC	whole	1983	14	4.36	8.81	6.68	1.28	6.86			(10)
α-BHC	whole	1986	31	1.173	5.919	4.115			0.011	0	(8)
lindane	dis.	<1986				2.0					(11)
lindane	part.	<1986				0.2					(11)
lindane	whole	1983	14	0.806	1.85	1.3	0.34	1.26			(10)
lindane	whole	1986	31	0.311	2.276	1.313			0.011	0	(8)

Table 15. *(Continued on following page)*

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Mirex	dis.	<1986			0.03						(11)
Mirex	part.	<1986			0.03						(11)
Mirex	whole	1983	14		ND					10	(10)
Mirex	whole	1986	31		ND				0.011	100	(8)
toxaphene	dis.	<1986				0.4					(11)
toxaphene	part.	<1986				0.2					(11)
toxaphene	whole	1981				0.6					(9)
toxaphene	whole	1983	14		ND					100	(10)
B(a)P	dis.	<1986				0.2					(11)
B(a)P	part.	<1986				0.1					(11)
HCB	dis.	<1986				0.04					(11)
HCB	part.	<1986				0.02					(11)
HCB	whole	1980	5	0.02	0.1	0.06			0.01		(7)
HCB	whole	1983	14	0.017	0.103	0.052		0.042		0	(10)
HCB	whole	1986	31	0.02	0.113	0.063			0.011	0	(8)
PCBs	dis.	<1986				0.6					(11)
PCBs	part.	<1986				0.3					(11)
PCBs	whole	<1981		2	50						(12)
PCBs	whole	1983	14	0.32	3.1	0.95	0.71	0.78			(10)
PCBs	whole	1986	31	0.484	5.189	1.41			0.24	0	(8)

ND : not detected
Sample : whole = whole water; dis.= aqueous phase; part.= suspended particulate phase.
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Neilson 1983. The range represents the mean concentrations for 3 cruises.
2. Nriagu *et al.* 1980. Particulate conc.: ppt=ng/L.
3. Traversy *et al.* 1975.
4. Stevens 1987. Offshore waters.
5. Rossmann and Barres 1988. The number presented for "% below detection" actually represents the percent of analyses below the limit or criterion of detection. Particulate concentrations are ng/L.
6. Chau and Saitoh 1973.
7. Oliver and Nicol 1982
8. Stevens and Nielson 1989.
9. Sullivan and Armstrong 1985
10. Biberhofer and Stevens 1987
11. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models. Part. conc.: ppt=ng/L. Particulate conc. + dissolved conc.= whole water conc.
12. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.

Table 15. Toxic chemical concentrations in Lake Ontario water (ppt).

et al. 1983). In 1983, the highest total PCB concentration (Table 15) was detected adjacent to Hamilton Harbour (Biberhofer and Stevens 1987). Concentrations of PCBs in Lakes Ontario and Erie were significantly higher than those of Lakes Huron and Superior. Locations identified as having high PCB concentrations in 1983 were Black River Bay (1.9 ppt) and the Niagara River plume (1.1 ppt) (Biberhofer and Stevens 1987). The central area of the lake in 1986

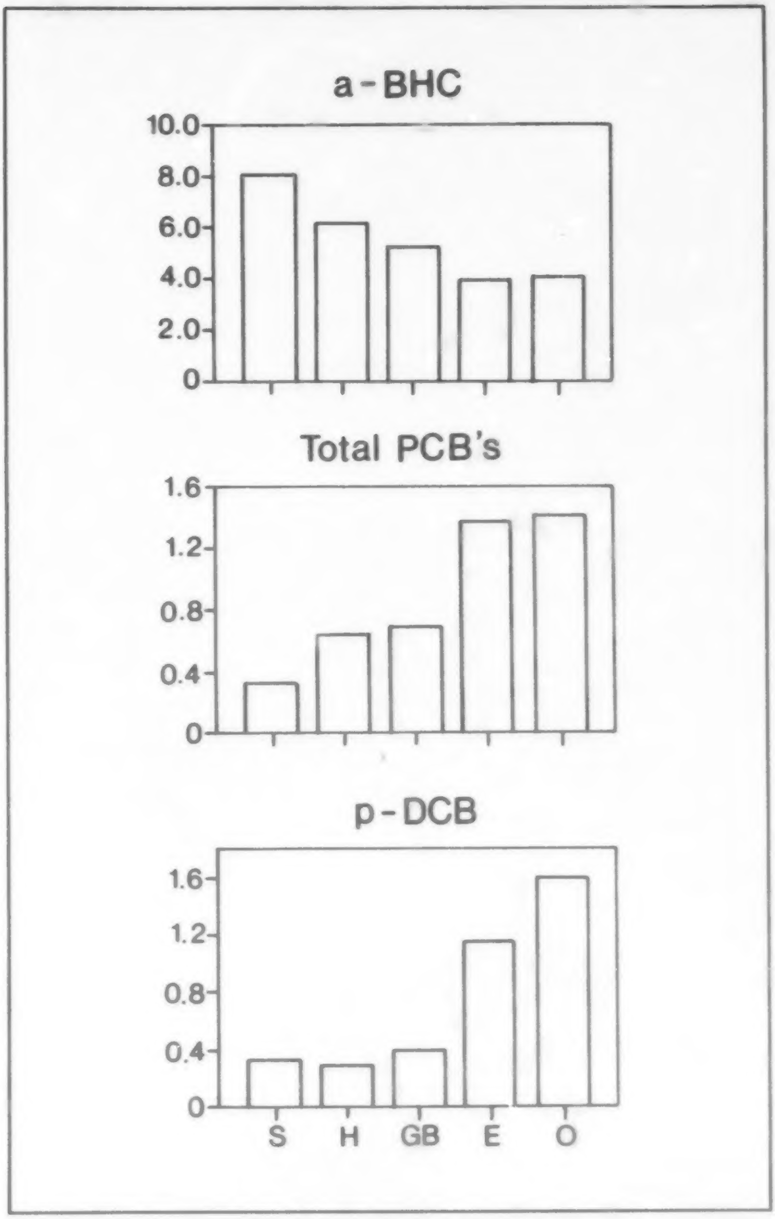

Figure 14. Inter lake comparison of mean concentrations of α-BHC, total PCBs and p-DCB (ng/L) (all compounds were detected at 100% of stations sampled in each lake). S - Superior; H - Huron; GB - Georgian Bay; E - Erie; O - Ontario (Stevens and Nelson (1989)).

had PCB concentrations of 1.5 to 2.5 ppt, higher than values nearer the north and south shores (Stevens and Neilson 1989). Chlorinated benzenes were higher in Lake Ontario waters in 1986 than in any other of the Great Lakes. In particular there are major differences in concentrations of di, tri, and tetra chlorobenzenes between Lake Erie at its inflow to the Niagara River and Lake Ontario off and to the east of the mouth of the Niagara River (Figure 14) (Stevens and Neilson (1989)).

An extensive nepheloid layer was described in Lake Ontario (Sandilands and Mudroch 1983) for depths greater than 60 m. Oliver and Charlton (1984) and Oliver *et al.* (1987) stated that resuspension occurred, especially during the winter months. At that time, Lake Ontario is unstratified and frequent violent storms can penetrate the lake to great depths. Oliver and Charlton (1984) found that given the amount of particulate matter available, the adsorption was low compared to theoretical partition coefficients and that concentrations of organic chemicals were generally higher in the suspended sediment fraction at deeper depths, indicating resuspension of bottom surface sediments. In 1981, Sandilands and Mudroch (1983) found that the suspended particulate concentrations of Pb were similar to the surface bottom sediment concentrations at the same locations.

Data on particulate metal concentration is given in Table 15. Most of the Pb in Lake Ontario water (approximately two thirds) was in the particulate fraction in 1978 (Nriagu *et al.* 1980) and 1985 (Rossmann and Barres 1988). In 1981, Sandilands and Mudroch (1983) found that the suspended particulate concentrations of mercury were less than the surface sediment concentrations at the same locations. Nriagu *et al.* (1980) reported higher particulate Cd concentrations in nearshore than offshore waters. When metal levels in each of the Great Lakes were compared (Rossmann and Barres 1988), Lake Ontario was found to have significantly higher particulate Cd than Lakes Superior, Michigan, and Huron. Generally the concentration of particulate Cd in Lake Ontario decreases from west to east due to sedimentation (Lum 1987). In 1981, Sandilands and Mudroch (1983) found that the suspended solids concentrations of As were less than the surface sediment concentrations at the same locations.

In 1981, one hundred percent of p,p'-DDT, 60% of p,p'-DDE, and 100% of dieldrin were in the aqueous phase in Lake Ontario (McCrea *et al.* 1985). Among all the chlorobenzenes, HCB has the highest tendency to become associated with suspended sediments and most of the HCBs in Lake Ontario are in the bottom sediments (Oliver 1984). Where Mirex was found in the lake, it was almost exclusively in the particulate phase (McCrea *et al.* 1985). In Lake

Ontario surface water, 91% of the PCBs were in the dissolved phase (McCrea *et al.* 1985). Concentrations of toxaphene and B(a)P in Lake Ontario were calculated by Strachan and Eisenreich (1988). No information was found for dioxins/furans in the particulate phase. McCrea *et al.* (1985) reported that α-BHC and lindane were almost exclusively in the aqueous phase.

Chemical Concentrations in Bottom Sediments: There are four sedimentation basins in Lake Ontario, named from west to east, Niagara, Mississauga, Rochester and Kingston. The major source of suspended sediment to the lake is the Niagara River. At the mouth of the river, sedimentation occurs off the Niagara Bar.

Concentrations of toxic chemicals in Lake Ontario bottom sediments are summarised in Table 16. Background levels of lead in Lake Ontario bottom sediments are 18–32 ppm. (Mudroch *et al.* 1985). In 1968, surface sediments were enriched approximately six times above background Pb levels (Thomas and Mudroch 1979). High concentrations of over 150 ppm conformed to the depositional basins indicating diffuse, rather than point sources (Thomas *et al.* 1988). Levels of lead in the bottom sediments of the depositional basins of Lake Ontario were significantly higher than those of Lake Huron and Lake Superior; and higher than those of Lakes Erie (Hodson *et al.* 1984). In a review of 1974–84 data, Mudroch *et al.* (1988) calculated that the range of Pb concentrations reported for the depositional zones for both Lake Ontario and Lake Erie were almost identical. Also, the range of concentrations completely enclosed (with much higher maximum values) those of Lakes Huron, Michigan and Superior. However, they noted that comparison of concentrations should be viewed with caution because of different sampling techniques employed. Background levels of mercury in sediments in depositional zones of Lake Ontario are 30–90 ppb (IJC 1987b). Background concentrations in the Niagara and Rochester Basins are more than twice that of the Mississauga Basin (IJC 1987b). The major source of anthropogenic Hg to Lake Ontario has been the Niagara River (Thomas 1972). Because of the effect of the lake currents on the Niagara River plume, the highest concentrations of Hg were found in sediment along the south shore and in an area to the northwest of the river mouth (Figure 3). Eadie *et al.* (1983) suggested that, as well as the Niagara River, significant local sources of mercury could also be involved. The range of background levels of Cd in Lake Ontario is 0.9–3.7 ppm (Mudroch *et al.* 1985). There has been an obvious post-industrial rise of Cd in bottom sediments. In 1968, there were many areas with concentrations greater than 6 ppm Cd in bottom sediments from both depositional

Chemical	Sample	Testing Date	#	Min	Max	Mean	SD	Median	DL	% <DL	Ref.
Pb	3 cm	1968	275	4,000	267,000	107,000	65,000				(5)
Pb	1 cm	?1968	5	176,000	285,000	220,000	36,000	216,000			(11)
Pb		<1981		<50,000	>150,000						(1)
Pb		<1984		7,000	285,000						(3)
Pb		<1986				100,00					(2)
Hg	3 cm	1968	275	25	2,100	651	511				(5)
Hg	1 cm	?1968	5	540	3,950	2,350	130	2,650			(11)
Hg		<1981		25	3,900						(1)
Hg		<1984		140	3,950						(3)
Hg		<1986				800					(2)
Cd	3 cm	1968	275	100	20,600	2,500	1,900				(5)
Cd	1 cm	?1968	5	3,700	6,200	5,100	320	5,100			(11)
Cd		<1984		100	6,200						(3)
Cd		<1986				1,000					(2)
As	3 cm	1968	275	200	22,500	3,300	4,700				(5)
As	3 cm	?1968	8	1,500	14,000	4,100	3,800	2,800			(4)
As		<1984		200	17,000						(3)
tDDT	3 cm	1968	229	0.5	218	42.8	42.4		0.4	0	(14)
tDDT		<1981				<50					(1)
tDDT		<1986				50					(2)
p,p'-DDE	3 cm	1968	229	0.5	70	12.7	12.5		0.1	0	(14)
DDE	3 cm	1981	6	26.8	130	62	42	86			(10)
dieldrin	3 cm	1968	229	ND	6.7	0.6			0.1	61	(14)
dieldrin		<1981				<3					(1)
dieldrin		<1986				10					(2)
Mirex	3 cm	1968	229	ND	40	7.5	6.3		1	67	(12)
Mirex		1980	8	Tr	62						(15)
Mirex	3 cm	1981	35	3	65	33	16				(13)
Mirex	3 cm	1981	6	45.7	110	86	25	95.5			(10)
Mirex		<1986				50					
α-BHC		<1986				2					(2)
lindane		<1986				5					(2)
B(a)P			1			306					(8)
B(a)P		<1986				300					(2)
HCB		1980	12	7.6	89						(15)
HCB	3 cm	1980	11	9	320	97					(9)
HCB	3 cm	1981	35	16	250	112	63				(13)
HCB	3 cm	1981	6	150	380	226	73	205			(10)
HCB	2 cm	1981	9	62	840	220	230			0	(16)
HCB		<1986				10					(2)
HCBD		1980	4	Tr	8.7						
HCBD	3 cm	1981	6	24	45	34	7	34			(10)
HCBD	2 cm	1981	9	12	120	35	32			0	(16)
PCBs	3 cm	1968	229	ND	280	57	56		5	4	(14)
PCBs		<1981		30	100	80					(1)
PCBs	3 cm	1981	35	200	1200	606	256				(13)
PCBs	3 cm	1981	6	630	1,500	844	420	975			(10)
PCBs	2 cm	1981	9	260	840	570	220			0	(16)
PCBs		<1986				100					(2)
OCDD		1963	1			4.8					(7)
TCDD	3 cm	198?	5	ND	0.004					80	(6)

Table 16. *(Continued on following page)*

Tr: trace abundance
ND : not detected
Sample : depth of surficial sediment sample
# : number of samples
SD : standard deviation
DL : detection limit
% <DL : percent below the detection limit

1. Sonzogni and Simmons 1981. Typical concentration range. These values are designed only to illustrate the types of values and the relative range of concentrations reported.
2. Strachan and Eisenreich 1988. Mean value based on assessment of historical data up to 1985–86. These values were used in mass balance models.
3. Mudroch *et al.* 1988. These numbers are a summary of concentration ranges taken from reports published between 1974 and 1984. Concentrations are from surface samples of depositititional zones.
4. Traversy *et al.* 1975. Depositional and non-depositional zones.
5. Thomas and Mudroch 1979. Depositional and non-depositional zones.
6. Onuska *et al.* 1983. Western Lake Ontario.
7. Czuczwa and Hites 1986
8. Eadie 1984
9. Oliver and Nicol 1982. Depositional and non-depositional zones.
10. Bourbonniere *et al.* 1986.
11. Kemp and Thomas 1976b
12. Holdrinet et al 1978. Depositional and non-depositional zones.
13. Oliver *et al.* 1987. Depositional zones.
14. Frank *et al.* 1979a. Depositional and non-depositional zones.
15. Kaminsky *et al.* 1983. Southwestern Lake Ontario.
16. Fox *et al.* 1983. Southwestern Lake Ontario.

Table 16. Toxic chemical concentrations in Lake Ontario bottom sediments (ppb).

and non-depositional areas (Thomas and Mudroch 1979). As of 1970–71, Cd levels were still increasing in the depositional basin sediments (Kemp and Thomas 1976a). Lake Ontario has the highest sediment Cd concentration of the Great Lakes (Lum 1987), approximately twice that of Lakes Michigan and Erie. Generally, Cd concentrations are higher in non-depositional zones and embayments (maximum levels of 18.6, 20.6, and 22.0 ppm respectively) than in the depositional zones (maximum level of 6.2 ppm) (Mudroch *et al.* 1985). Background levels of As in Lake Ontario are not available. Mudroch *et al.* (1985) reported that surface sediment levels in depositional and non-depositional zones from the late 1960s early 1980s were 0.2–17.0 and 0.2–24.0 ppm respectively.

In 1968, Frank *et al.* (1979a) found ΣDDT and dieldrin mainly in the surface bottom sediments of the depositional basins of the lake (Table 16). In 1981, the highest concentrations of DDT were found in bottom sediments along the western shore of the Kingston Basin (Stevens 1987). In 1980, Oliver and Nicol (1982) reported CB concentrations in Lake Ontario sediments (Table 16) to be much higher than in Lakes Superior, Huron, and Erie (10–38 ppb). Also, the higher chlorinated CBs, associated with industrial activity, were more common in Lake Ontario than in the other lakes. In a 1981 surficial sediment survey, Oliver *et al.* (1987) found mean concentrations of HCB for the Niagara, Mississauga, Rochester and Kingston Basins to be 110, 130, 100, and 14 ppb respectively. In 1968, Holdrinet *et al.* (1978) observed areas of sediment with Mirex concentrations of over 10 ppb extending from the Niagara and Oswego Rivers (Figure 15). The mean concentration of Mirex in surficial sediments in 1968 was 7.5 ppb (Holdrinet *et al.* 1978). By 1977, large areas of the lake had concentrations of Mirex over 20 ppb (Thomas *et al.* 1988). The mean concentration in 1981 was 33 ppb (Oliver *et al.* 1987) based on fewer samples all from the depositional basins. Pickett and Dossett (1979) predicted that by 1989 the highest concentrations of Mirex would be in two plumes: at the mouth of the Niagara River and along the southern shore and adjacent to the mouth of the Oswego River, respectively. Eadie *et al.* (1983) predicted that the plume would move from the southern shore to the south-eastern shore and then to the Niagara and Rochester basins. The predictions made by Eadie *et al.* (1983) are closer to the results reported by Oliver *et al.* (1987), namely that by 1981 Mirex was becoming more evenly distributed in the sedimentary basins. No toxaphene values have been reported for Lake Ontario sediments (Strachan and Edwards 1984). Onuska *et al.* (1983), calculated that PAHs introduced to the lake from the Niagara River generally moved to the east.

The congener profiles of PCDDs and PCDFs in Lake Ontario sediments were different from the other Great Lakes because of the high concentration of OCDF present (Czuczwa and Hites 1986). The presence of OCDF indicates a local source which could be from the production of HCB and pentachlorophenol (PCP). HCDF, HpCDF, OCDF, and 2,3 7,8-TCDD were all detected in sediments offshore from the mouth of the Niagara River in the early 1980s (Onuska *et al.* 1983; Kaminsky *et al.* 1983). The maximum concentration for 2,3,7,8-TCDD in bottom sediment was 13 ppt (Onuska *et al.* 1983).

In 1968 mean PCB concentration was generally higher (85 ppb) in the depositional than non-depositional (28 ppb) basins. The mean value for the whole lake was 58 ppb ($n = 216$). A plume of >200 ppb PCBs extended from the mouth of the Niagara River. Minor plumes indicated other local sources along the north and south shores (Frank *et al.* 1979a; Thomas and Frank 1983) (Figure 4). The 1981 mean PCB concentrations (Oliver *et al.* 1987) were considerably higher (570 ppb) than those of 1968 (58 ppb). Improved extraction and analytical techniques are the probable explanation.

In 1970–71 sediment cores showed anthropogenic surface enrichment of Hg, Pb, Zn, Cd, and Cu at all five stations in Lake

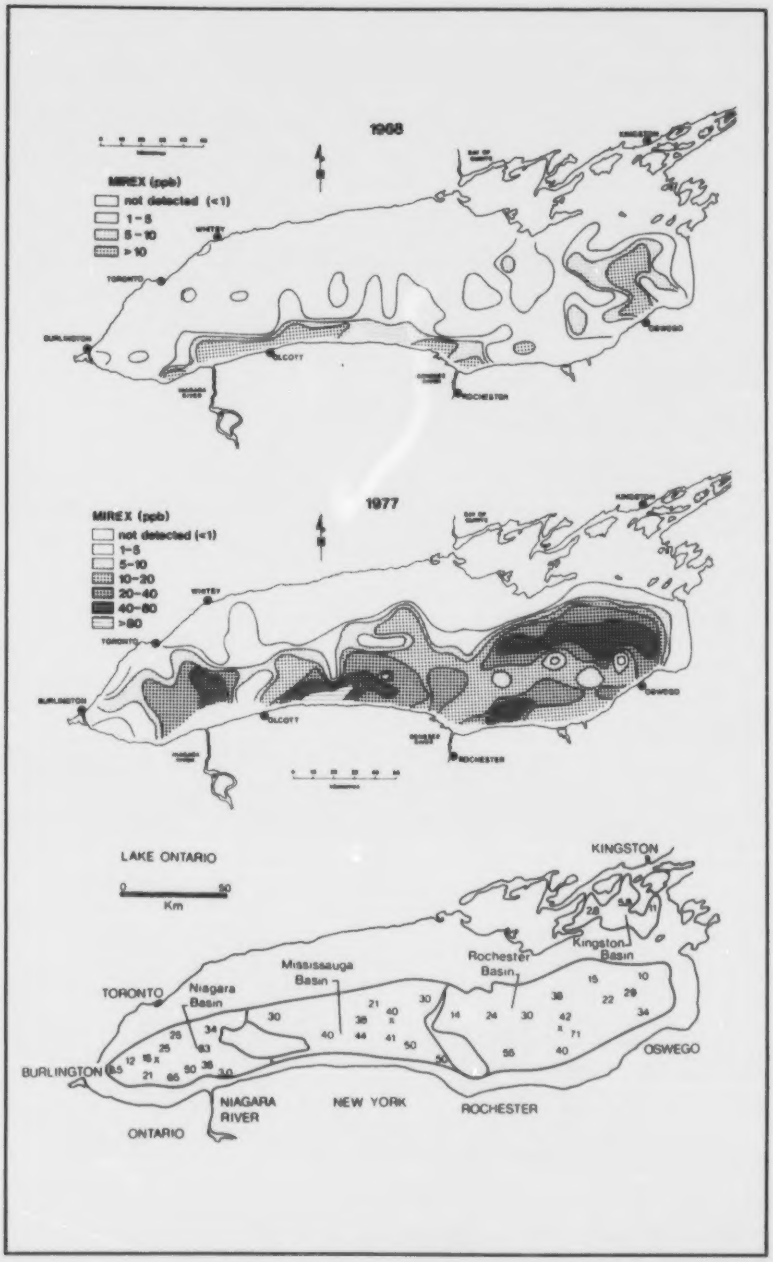
1968
MIREX (ppb)
not detected (<1)
1-5
5-10
> 10
WHITBY
TORONTO
BURLINGTON
OLCOTT
ROCHESTER
OSWEGO
KINGSTON
1977
MIREX (ppb)
not detected (<1)
1-5
5-10
10-20
20-40
40-80
>80
WHITBY
TORONTO
BURLINGTON
OLCOTT
ROCHESTER
OSWEGO
KINGSTON
LAKE ONTARIO
0
50
Km
KINGSTON
Kingston Basin
Rochester Basin
Mississauga Basin
Niagara Basin
TORONTO
BURLINGTON
OSWEGO
NIAGARA RIVER
NEW YORK
ROCHESTER
ONTARIO

Figure 15. Concentration of Mirex (ppb) in 3 cm surficial sediments of Lake Ontario. (a) 1968 (Holdrinet *et al.* 1978); (b) 1977 (Thomas *et al.* 1988); and (c) 1981 (Oliver *et al.* 1987).

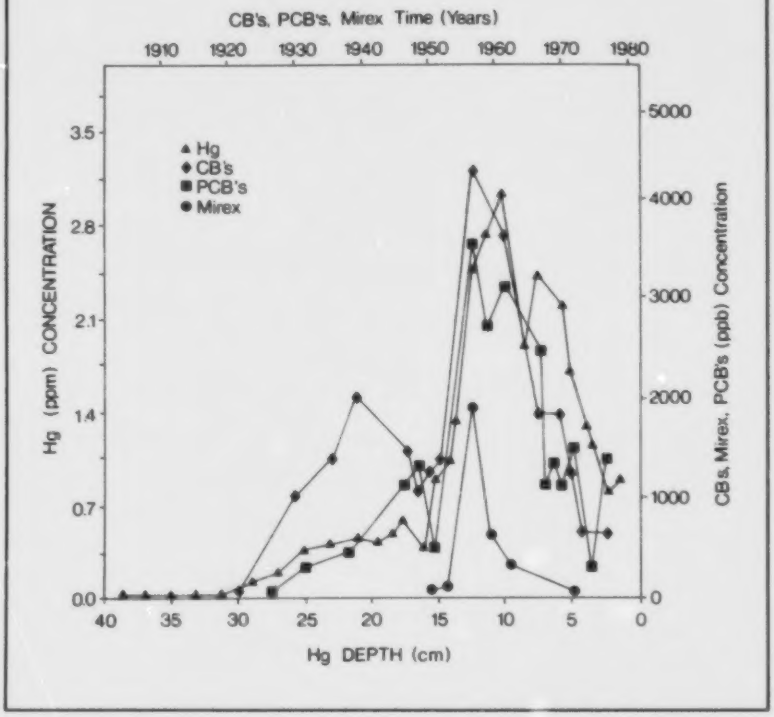

Figure 16. Distributions of Mirex, CBs and PCBs in Niagara River delta sediment cores (after Durham and Oliver 1983) and distribution of Hg in an eastern Lake Ontario sediment core (after Eadie *et al.* 1983).

Ontario (Kemp and Thomas 1976a). In 1981, two cores taken from the eastern end of the lake were shown to have subsurface maximum concentrations of Hg (Figure 16) and Pb. However, surface levels (120–150 ppm) were still considerably higher than background (Eadie *et al.* 1983). The cores indicated that the average Pb flux to Lake Ontario increased 680% from the early 1800s to the time of maximum lead usage in the mid-1970s (Eadie *et al.* 1983). Surface sediment Pb levels are still elevated at 100–200 ppm near the Niagara River mouth in the early 1980's (Mudroch 1983). Recovery from mercury pollution, as seen in sediment cores, was the most dramatic for the toxic metals (Mudroch 1983; Mudroch *et al.* 1988). In a core taken in 1970, mercury contamination was shown to increase rapidly between the turn of the century and the early 1940s. Between then and

1970, mercury concentrations increased at a slower rate and were in the range of 1–1.5 ppm (Thomas 1972). This dramatic increase was also seen in cores sampled 1970–71 from the depositional basins. Surface concentrations were reported as being higher for the Niagara and Rochester Basins than for the Mississauga Basin. The surface sediment concentration range for the three basins was 2.6–3.9 ppm (Kemp *et al.* 1974). Cores taken in 1981, from both ends of the lake showed a reversal of this trend (Eadie *et al.* 1983; Mudroch 1983) (Figure 16). Immediately adjacent to the mouth of the Niagara River, subsurface maximum Hg concentrations ranged from 4–7 ppm. Surface levels were approximately 1 ppm. Ranges in the eastern cores were slightly lower. The Hg distribution shows that this site of former maximum surficial sediment Hg concentration now has surface sediment concentrations less than those of surficial sediments farther out in the lake. The presently more contaminated sediments remain well within benthic organism mixing depths, whereas the former maximum concentrations near the Niagara River mouth are now below this depth (Allan 1986).

In 1976, cores showed the highest concentrations of DDT in the surface sediments and first appearance in the late 1950s (Frank *et al.* 1979a). In a 1982 core, peak levels of DDT were again seen in the late 1950s to the early 1960s, in good agreement with usage patterns (Oliver *et al.* 1987). Oliver and Nicol's (1982) core showed that increases of CBs in sediment began in the early 1940s and began to decline by the late 1960s (Figure 16). This corresponds to the use of CBs in the production of phenols. There was little, if any, change in the the proportions of the various chlorobenzenes down this core. Cores analysed by Onuska *et al.* (1983) also showed that there may have been a decrease in chlorobenzene loading from the Niagara River during the 1970s. HCBD and OCS concentrations in cores also peaked (160 ppb and 550 ppb respectively) in the 1960s and 1970s respectively. Low concentrations of HCBD occurred prior to the late 1950s and after the early 1970s, with high concentrations during the 1960s (Durham and Oliver 1983). Sediment core analyses reflected Mirex production in the Niagara River area (Durham and Oliver 1983; Eadie *et al.* 1983) (Figure 16). Because concentrations continued to increase and expand in the lake sediments after production ceased (in 1976), remobilization of contaminated Niagara River sediments has been suspected (Thomas *et al.* 1988). Durham and Oliver (1983) found the highest concentrations of PCBs to be at sediment depths corresponding to early 1960s (Figure 16). Sediment core samples showed up to a 100 times increases in PAH's in the surface over deeper sediments, indicating extensive loading in the late 1970s.

St. Lawrence River

The St. Lawrence River drains Lake Ontario and thus the Great Lakes to the north Atlantic ocean. The St. Lawrence River has a massive flow out of Lake Ontario of some 7,700 m^3/sec. The mean concentration of suspended solids in the river at its source in Lake Ontario was 1.3 mg/L (mean of four years of data). The international section of the river included in the Great Lakes Water Quality Agreement stretches from Lake Ontario to the Province of Quebec and thus does not include Lake St. Francis. Major industries are located on the Canadian and United States shores of the river just upstream from Quebec. They include a major foundry, automobile plant, and two large aluminium plants. In the Cornwall area, a former chor-alkali plant released Hg to the St. Lawrence and resulted in high Hg levels in downstream bottom sediments. Near Maitland, a former tetraethylead plant was a source of alkylleads to the river.

Chemical Concentrations in Water and Suspended Solids: In the St. Lawrence River in 1977, the mean concentrations of the metals discussed here were 0.50 to 1.01 ppb Pb; ND-0.004 ppb Hg; beneath detection for Cd; and 0.55–0.73 ppb As between Kingston and Cornwall (Chan 1980). These results were based on unfiltered water. Between 1977 and 1983, water samples from the St. Lawrence outflow from Lake Ontario were routinely analysed for inorganic chemicals (Sylvestre *et al.* 1987). Values less than the detection limit were taken as equal to the detection limit for calculation of means. The mean concentrations for Pb between 1977 to 1983 was 1.2 ppb ($n = 341$). No data was given for Hg, Cd or As. Between 1979 and 1982 filtered water samples showed that Hg concentrations at Cornwall-Massena were below 0.2 ppb. The metal most studied recently in the river has been Cd. Lum and Kaiser (1986) reported dissolved Cd concentrations of 3–23 ppt (mean = 10 ppt; $n = 11$).

In 1977, lindane and α-BHC, were detected in water in the St. Lawrence between Kingston and Cornwall at concentrations from 3 to 7 ppt and 3 to 8 ppt respectively (Chan 1980). In 1982, water and suspended sediments collected at the source of the St. Lawrence River near Wolfe Island, began to be analysed routinely for toxic organic chemicals (Sylvestre 1987). The chemicals determined were PCBs, PAHs, CBs and organochlorine pesticides. In whole water, only 3 of the 18 organochlorine pesticides measured were detected in more than 40% of the samples. Mean concentrations for 1982 to 1984 were 5.8 ppt α-BHC; 1.0 ppt lindane; and 0.4 ppt dieldrin (Sylvestre 1987). The results for <40% detection were not considered meaningful to calculate means using the detection limit as the lower value. When larger volume samples (200 L versus 2 L) were extracted in 1983, other chemicals were detected above the improved detection limit. The results from this 1983 study were 4.8 ppt α-BHC, 1.2 ppt lindane; 0.54 ppt dieldrin (all similar to the above); 0.17 ppt total DDT; and 0.43 ppt total PCBs. Mirex remained beneath detection. McCrea *et al.* (1985) found that DDT and its metabolites were from 38 to 100% in the aqueous phase in the St. Lawrence River. Concentration of pp-DDT was 0.065 ppt in the aqueous phase and 0.02 ppt in the suspended solids, while PCB's were present at 2.0 ppt in the aqueous phase and at less than 0.1 ppt in suspended solids. In 1977, PCB's were detected in water at the mouth of the Grassé River at concentrations of 60 and 180 ppt. Levels of 20 to 70 ppt in water and up to 660 ppb PCBs in suspended solids were measured at the mouth of the Grassé River between 1979 and 1982 (MOE 1988a).

Lum and Kaiser (1986) reported particulate Cd concentrations of 1.0 to 3.8 ppm (mean = 2.1 ppm; n = 12) for 1985. Between Cornwall and Massena, suspended solids had Hg concentrations of up to 2.4 ppt in 1979–82. Between Kingston and Cornwall, Merriman (1987) reported concentration ranges in suspended solids of <1–2 ppb α-BHC; <1 ppb lindane; <1–14 ppb dieldrin; <1–16 ppb p,p'DDT; 7–18 ppb p,p'DDE; 11–34 ppb total DDT and metabolites; <1 to 6 ppb Mirex; 1–27 ppb HCB; and 30 to 126 ppb total chlorobenzenes in 1981. The spatial distributions of total DDT and metabolites, total PCB's and Mirex are given in Figure 17. Between 1982 and 1984, lindane was beneath the detection limit of 4 ppb while α-BHC and dieldrin were detected in more than 40% of the samples at mean concentrations of 6 ppb and 9 ppb respectively in suspended solids collected at Wolfe Island (Sylvestre 1987). PCB's were detected in 93% of the samples at a mean value of 162 ppb. Total DDT was found in 90% of the samples at a mean concentration of 18 ppb. Mirex was detected in 33% of the samples and concentrations ranged from beneath the detection limit of 4 ppb to a maximum of 27 ppb. A mean for Mirex could not be reasonably calculated with 33% detection but the mean of the concentrations above detection was 9.8 ppb (n = 26). In 1981, the range of Mirex concentrations had been from beneath detection to 6 ppb (Figure 17). The occurence of some chlorinated benzene congeners in suspended solids was >50%. The mean concentrations, maximum values are in brackets, were 32 ppb (131) 1, 2, 4-tri; 14 ppb (95) 1, 2, 3, 4-tetra; 11 ppb (56) penta; and 13 ppb (54) hexachlorobenzene (Sylvestre 1987). Most PAH's were not detected in the suspended solids at a detection limit of 50 ppb and the few exceptions were possibly the result of interference in the analyses.

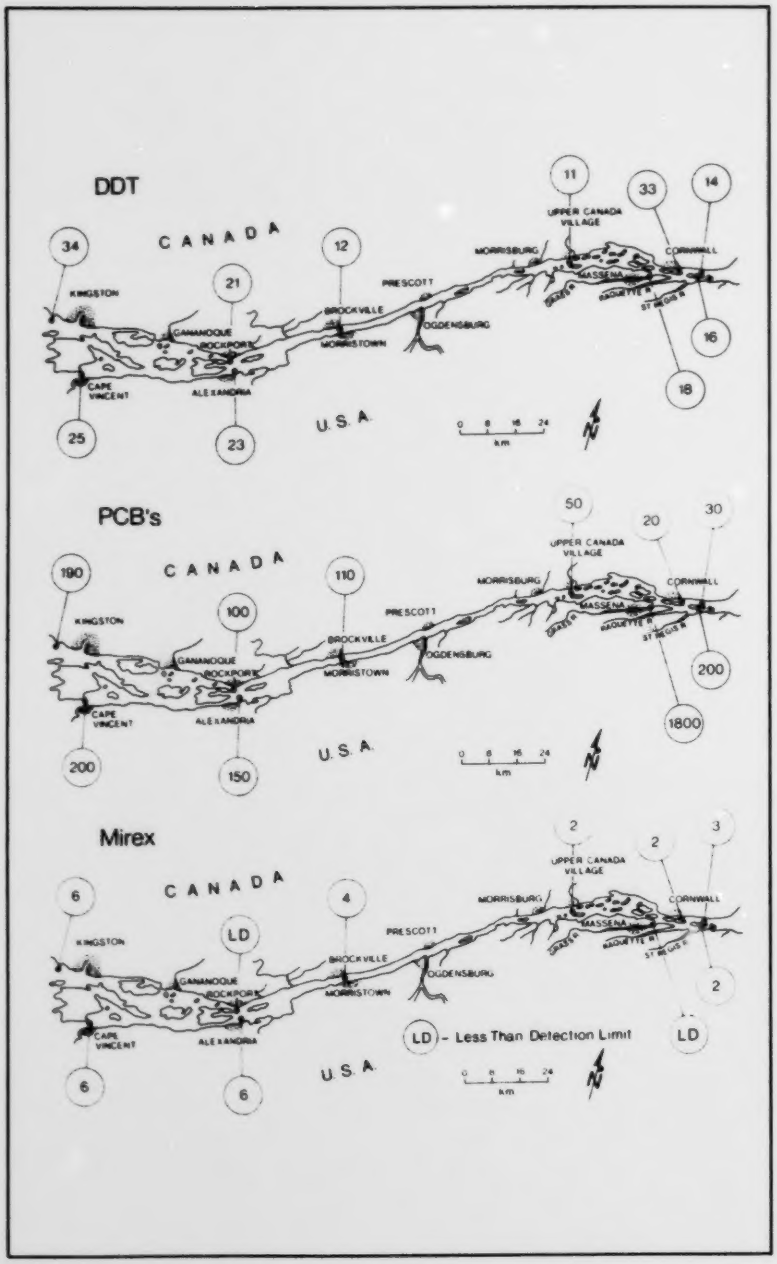
DDT
CANADA
U.S.A.
34
21
12
11
33
14
16
18
25
23
KINGSTON
GANANOQUE
ROCKPORT
BROCKVILLE
MORRISTOWN
PRESCOTT
OGDENSBURG
MORRISBURG
UPPER CANADA VILLAGE
CORNWALL
MASSENA
GRASSE R
RAQUETTE R
ST REGIS R
CAPE VINCENT
ALEXANDRIA
0 8 16 24
km
N
PCB's
CANADA
U.S.A.
190
100
110
50
20
30
200
1800
200
150
Mirex
CANADA
U.S.A.
6
LD
4
2
2
3
2
LD
6
6
LD - Less Than Detection Limit

Figure 17. Total DDT and metabolites; PCBs and Mirex in suspended solids in the St. Lawrence River in 1981 (after Merriman 1987).

Chemical Concentrations in Bottom Sediments: In 1975, Kuntz (1988a) collected bottom sediments between Kingston and Cornwall and Cape Vincent and Masenna on the Canadian and United States sides of the St. Lawrence River. Pb concentrations ranged from the detection limit of 50 ppm up to 190 ppm. Mercury concentrations were usually well below 0.3 ppm, except for a site immediately downstream of Cornwall where the concentration was 4.9 ppm. Concentrations of Cd were generally below the detection limit of 10 ppm. Five of fifty-six samples were above detection and the maximum Cd value was 14 ppm just downstream of the Grassé River. For As, the concentrations ranged up to 7.6 ppm on the Canadian side and 8.0 ppm on the United States side of the river.

In 1975, p,p'-DDT was not detected in any of the 57 samples analaysed (Kuntz 1988a). For p,p'-TDE several concentrations above the detection limit, in the range of 3–11 ppb, were observed in the Gananoque-Rockport area; p,p'-DDE was usually below the detection limit of 1 ppb and its maximum concentration was 90 ppb. In 1981, the highest concentration of total DDT and metabolites was 56 ppb just off Kingston (Merriman 1987) (Figure 17). The maximum HCB concentration detected in 1981 was 13 ppb for the seven sites sampled (Merriman 1987) and the values were in the Dupont outfall zone near Maitland (MOE 1988b). The bottom sediment survey of 1975 did not detect Mirex in any of the samples at a detection limit of 1 ppb (Kuntz 1988a). In 1981, Merriman (1987) detected Mirex at only one site near Kingston at 9 ppb. In 1975, Kuntz (1988a) found levels of PCB's above 50 ppb at 10 of 57 stations. The highest value was 1.5 ppm downstream of the Grassé River. In 1981, the highest bottom sediment PCB concentration was 8.74 ppm (Merriman 1987). Total chlorobenzenes were found in low concentrations of 8–9 ppb in St. Lawrence River bottom sediments (Merriman 1987). The maximum concentration was 50 ppb.

Conclusions

The purpose of this report was to give an overview of toxic chemical concentrations along with historical concentration trends in water and sediments of the Great Lakes. Until recently we have relied on analyses of bottom sediments and in particular cores of bottom sediments as a surrogate method to detect trends in chemical inputs and concentrations in water in the lakes. This is easier to do for chemicals in sediments than water because of historical problems in analysis of waters for the extremely low ambient concentrations that existed. From the available sediment data, the trends for the chemicals discussed all seem to be downwards at least relative to the concentrations 10 and 15 years ago. Thus, the historical trends of chemical concentrations in lake bottom sediment cores indicate that the major influx of toxic metals and persistent toxic organic chemicals to the Great Lakes aquatic ecosystem took place in the nineteen sixties and early seventies. These peak concentrations are followed by declines into the early eighties. Some of these declines have been dramatic, once control action has taken place (PCBs; Mirex). Often, these periods of peak input of several chemicals to the Great Lakes occurred several years prior to their first detection in lake media. Thus, the overall evidence from the abiotic data is that the maximum inputs of most of those toxic metals and persistent, chlorinated, organic chemicals so far detected occurred in the past and that the inputs of such chemicals have declined, often dramatically in recent years. There are some exceptions along the St. Clair River-Detroit River corridor and the Niagara River where concentrations are at a plateau rather than declining.

Trends

Some changes in concentrations of contaminants over time have been determined for each of the lakes and channels. In Lake Superior, historic data for concentrations of Pb, Hg and Cd could not be used to determine trends in the waters. Arsenic concentrations in whole water declined since the 1970s. There has been a dramatic reduction in PCB concentrations in the waters and sediments of Lake Superior since the early to mid-1970s. Of the metals discussed in this report, Pb in sediments had a higher anthropogenic enrichment factor than Hg, Cd and As. In recent core analysis, Pb and Hg are shown to be decreasing in the surface sediments. Historic data for concentrations of Pb, Hg and Cd in Lake Michigan could not be used to determine trends in the waters. Arsenic concentrations in whole water declined since the 1970s. Pb has decreased in the sediments from high levels in the 1950s–1960s. Cd has shown similar declines from highs in the 1940s–1960s. PCBs have declined from peak levels in the 1960s–1970s. In Lake Huron, historic data for Hg, Cd and As in water could not be used to determine trends. Dissolved Pb concentrations have declined in Lake Huron. There are indications that levels of Pb, Cd and DDT in the water of Saginaw Bay have declined since the 1970s. In cores taken prior to 1980, there was surface enrichment of Pb, Hg, Cd and As. Hg in most parts of the St. Clair River has decreased in the bottom sediments, however, levels are often still above the dredging guideline. Core studies have also shown slight declines in sediment concentrations of HCB, HCBD and PAHs. For Lake St. Clair, PCBs, Hg and DDT decreased in bottom sediments following curtailment of use in the early 1970s. The concentrations of HCB and HCBD in the sediments of Lake St. Clair are still increasing or at least not dropping significantly. Generally, Hg has decreased in the bottom sediments of the Detroit River, however, levels are often still above the dredging guideline. In Lake Erie historic Pb data could not be used to determine trends in the water. Hg, Cd and As concentrations in water are decreasing. PCBs may be decreasing in the water of Lake Erie. Cores collected in the early 1970s showed anthropogenic increases of Pb, Hg and PCBs. More recent cores showed surface declines of Pb, As, DDT and metabolites, dioxins and furans. PCBs may not be declining in the sediments. During the 1980s, point source loadings to the Niagara River declined by over 60% on each side of the river. Because of changes in analytical methods, water samples from the early 1980s could not be compared to those of the mid-1980s. Between the mid-1970s and the 1980s, Pb loadings from the Niagara River to Lake Ontario were reduced by half. Peak levels of Hg in the sediments of the delta occurred in the early 1950s. By the end of the 1970s, Hg levels were back to pre-1940 levels. From the late 1960s to the early 1980s, Mirex and PCBs in surface sediments of Lake Ontario appeared to increase; however, improved analytical and sampling techniques are the probable explanation because core analyses refute this. Core analysis showed anthropogenic enrichment of Pb, Hg, Cd, DDT, CBs, HCBD, OCS, Mirex, PCBs and PAHs in bottom sediments but concentrations are now declining or levelling off. In the St. Lawrence River, Pb and Hg concentrations in sediments have declined following closure of source industries.

Interlake and Interchannel Comparisons

The most chemically contaminated Great Lakes were lakes Ontario, Michigan, and Erie based on an assessment on overall concentrations of toxic and persistent chemicals in abiotic aquatic media. Lake Superior was and is the least contaminated of the Great Lakes. Lake Huron is one of the least contaminated of the lakes with the exception of some local areas.

Sources and Physical Characteristics: The types of sources and the physical characteristics of the lakes and channels influence the relative concentrations in each area. The atmosphere is a greater source of most of the critical toxic chemicals to the upper Great Lakes than the lower lakes; for example, PCBs, DDT and Pb. The large surface areas and drainage basins of the upper lakes are major contributing factors. Conversely, the lower lakes receive greater inputs from their main tributaries, industries, municipalities and agriculture than the upper lakes. Concentrations tend to be similar throughout the Great Lakes when sources are only atmospheric and/or sediment resuspension; for example, dieldrin and toxaphene. Total suspended matter concentrations from highest to lowest are Lake Erie, Lake Ontario, lakes Huron and Michigan, and Lake Superior. Sedimentation rates are highest in Lake Erie followed by lakes Ontario and Michigan followed by lakes Huron and Superior. Higher total suspended matter and sedimentation rates are known to reduce bioaccumulation of contaminants and accelerate natural self cleansing of the lakes. Lake Michigan and Lake Superior have long water residence times which means that most of the chemicals introduced into these lakes are not quickly passed on downstream.

Water Concentrations: There was considerable variation in the water concentrations throughout the Great Lakes. The total concentrations of metals in water from highest to lowest are Lake Michigan, Lake Erie, Lake Ontario, Lake Huron, and Lake Superior. Of the trace elements, no concentrations in Lake Superior are higher than the other lakes except dissolved As in Lake Huron and particulate Cd in Lake Michigan. The trace element levels in Lake Huron are also consistently less than the other lakes. In the mid-1970s, PCB concentrations in suspended solids of the Detroit River were ranked with Niagara River as the highest levels in the Great Lakes. In the mid-1980s, Lake Ontario generally had higher concentrations of toxic organic chemicals in whole water than lakes Superior, Huron and Erie. The mean concentrations of CBs and lindane ranked highest in Lake Ontario. Concentrations of PCBs, p,p'-DDE, CBs and α-BHC were higher in lakes Ontario and Erie than lakes Superior and Huron. Whole water concentrations of CBs, dieldrin, and PCBs were similar in lakes Superior and Huron. Dieldrin, lindane and toxaphene were found to be ubiquitous. Mirex is generally not detected in the waters of the Niagara River and Oswego Harbour (Lake Ontario).

Sediment Concentrations: There were also variations in sediment concentrations. In the sediment survey of the late 1960s–early 1970s, toxic metal concentrations of Pb, Hg and Cd in the lower lakes were higher over greater areas of the lake bottom than for the three upper Great Lakes. Pb enrichment in Lake Superior is less than for the other Great Lakes. Information about As concentrations in Great Lakes sediments is scarce. In 1980, levels of HCB in the sediments were much higher in Lake Ontario than in lakes Superior, Huron and Erie. PAH concentrations in sediments are about 10 times lower in Lake Superior than the other Great Lakes reflecting both its remote location and the primarily atmospheric source. There has been an indication of recent declines in the level of B(a)P in Lake Superior and the St. Marys River. Lake Michigan has high levels of PAH concentrations in the sediments. The main source of dioxins and furans to the Great Lakes sediments is municipal and/or industrial combustion of chlorinated organic products present in various wastes. There was a predominance of OCDD and HpCDF. The highest concentrations of OCDD were in Lake Ontario followed by Lake Erie and lakes Michigan and Huron. Lake Ontario also had elevated levels of OCDF indicating a local source.

Intralake and Intrachannel Contaminant Patterns

The geographic contaminant pattern in the water of lakes is characterized by higher concentrations in the nearshore areas and in sediments by higher concentrations in the depositional basins, harbours and deltas. In the connecting channels, higher concentrations of contaminants are usually found along the shore downstream from sources. There are still increases in some chemicals along the courses of the connecting channels, especially along the St. Clair-Detroit River corridor and the Niagara River.

In Lake Superior, concentrations of organics have been found to be higher in the northern part of lake than the southern part. Elevated levels of Pb, Hg and Cd have been reported for some of the bays and harbours. All Rossmann's metal concentrations in Lake Superior were below the GLWQA objectives. Highest levels of toxic chemicals in the St. Marys River were generally found along the Canadian shore. For Lake Michigan, concentrations of toxic organic chemicals are usually higher in the southern section of the lake and Green Bay. PCB concentrations are highest in the sediments of the southwest part of the lake. Saginaw and Georgian Bays are the major sources of toxic chemicals to Lake Huron. In the St. Clair River elevated toxic chemical concentrations are confined primarily to a 100 meter wide area along the Ontario shore near Sarnia's chemical industrial area; for example, PCBs, volatile hydrocarbons, Pb and Hg. Spills are a significant problem. Increases in water and/or sediment concentrations over the course of the river have been reported for Pb, Hg, HCB, HCBD, OCS, and PAHs. Levels above the GLWQA objectives have been found for Pb, HCB and HCBD, and above dredging guidelines for OCS, PAHs and PCBs. For Lake St. Clair, PCBs have been reported as highest on the western side. Elevated levels of sediment contaminants have been found in the central depositional basin and at the outlet. In the Detroit River the majority of sources are along the U.S. shore and along the Rouge River. Chemical concentrations in water and/or sediment which have been reported to increase along the river are Cd, PCBs, CBs, dieldrin, lindane, industrial volatile halocarbons and PAHs. Levels above dredging guidelines have been reported for Pb. Hg, Cd, As, PCBs, PAHs, α-BHC, and lindane. The western basin of Lake Erie is the most impacted by toxic chemicals mainly because of inputs from the Detroit River; for example, PCBs and industrial halocarbons in water; PCBs, HCB, HCBD, and PAHs in sediments; and DDT and metabolites, Hg and Cd in sediments in the 1970s. The main sources of toxic chemicals to the Niagara River are along the U.S. shore. Concentrations of many contaminants are higher in the water and sediments of the Tonawanda Channel than the Chippawa Channel. Since there is extensive mixing at Niagara Falls, no plume develops. Increases along the course of the river were observed in the late 1970s–1980s for PCBs, α-BHC, lindane, CBs (sometimes including HCB), HCBD, Mirex, p,p'-DDE, Hg, Cd, As, PAHs and B(a)P. Sources of dioxins and furans have also been found. Concentrations for Hg, As, PCBs, Mirex, HCB and HCBD are much lower in the sediments of Lake Erie than those of Lake Ontario. DDT and metabolites have recently been shown to decrease between Fort Erie and Niagara-on-the-Lake. For Lake Ontario, the Niagara River has historically been the main source of toxic chemicals. These chemicals initially collect in a pattern in the sediments which reflects lake circulation. Eventually they reside in the depositional basins. Along with other dioxins and furans, 2,3,7,8-TCDD has been detected in the sediments offshore from the mouth of the Niagara River.

Data Reliability

The historically documented higher concentrations for metals in water are now thought to reflect sampling and particularly analysis in non-metal free (dusty) environments. The use of special sampling and clean laboratory techniques is now revealing that dissolved concentrations of Pb, Cd and other metals are much less (in the low ppt range) than previously thought (in the low ppb range). Likewise recent sampling techniques using large volume aqueous phase or continuous flow extraction systems have allowed reliable detection of toxic organic chemicals at extremely low concentrations (<1 ppt) in water samples. Historical data on toxic organic chemical concentrations in water mostly included non-detected concentrations or resulted in high concentrations which now must be viewed with caution.

If the values recorded are taken at face value then there have been dramatic reductions in some chemicals such as Pb, Cd and PCBs in some of the lakes. Declines in concentrations over the last few years are probably realistic. The most recent data, obtained for both toxic metals and organic chemicals is considered the most reliable and shows that ambient concentrations are very low, much lower than historically measured and thus believed.

Nearshore/Offshore Variations

Data on the types of toxic chemicals discussed here is rare for nearshore areas. There is data for the connecting channels and the concentrations of chemicals in water in these channels can vary considerably over short periods of time. The same would be true at nearshore sites if they were located under the influence of tributaries or effluents from industry or municipalities. Data on the nearshore areas of Canada is in the process of being acquired under the Remedial Action Plans (RAPs) for Areas of Concern (AOCs) and under the Ontario Municipal and Industrial Strategy for Abatement (MISA) Programmes.

There is no simple relationship between raw water toxic chemical content and that of drinking water taken from the Great Lakes. Drinking water intakes are all located nearshore, often within a kilometre or less of the shoreline. Wave action or storms can resuspend nearshore sediments or cause upwelling of deeper lake water on an event basis or can cause small creeks to dramatically increase their sediment load to the nearshore zone. In essence, each site is unique since it may be near a major municipal effluent or a unique industry. Drinking water treatment plants are designed to take these local variations into account by filtering the raw water and by removing suspended and probably colloidal material by flocculation. Thus, from a human exposure viewpoint, nearshore ambient toxic chemical concentrations are best assessed by analyses of treated drinking water. The only entirely Canadian Area of Concern from which drinking water is taken is the Bay of Quinte and toxic chemicals are not the main reason for this Bay being an AOC.

The open water data presented here is a better measure of total lake contamination and can be better used for comparison with information obtained by analysis of open lake fish. However, there is no simple relationship between the concentrations of chemicals in water and sediments and the concentrations in biota in the lakes.

Some scientists claim that the majority of chemicals are taken up directly by fish from the water by bioconcentration. Others favour the concept that the chemicals are primarily bioaccumulated in the food chain. For biota which inhabit contaminated sediments or for fish which eat organisms living in such sediments, the sediments or their porewater may be a major source of chemicals. For some fish it may well be all three, i.e. water, sediments, and other biota. The mix will be different for different organisms, at different trophic levels, with different diets and dependent on local contamination.

Present State of the Environment

In the last eight years (1982 to 1990) no new contaminants which fit the criteria of widespread occurrence, high toxicity, and long persistence, similar to the chemicals discussed in this report, have been detected in any of the Great Lakes. There are analytical techniques that could detect other chemicals, for example highly toxic but rapidly degraded pesticides, but the scale of the problem in space and time is unlikely to ever be as bad as it once was. To a greater extent than in the past, control actions will have to take into account the non-point sources of the chemicals, especially from atmospheric sources; chemicals recycled internally from in-situ contaminated sediments; agricultural, forestry and urban sources; and groundwater sources. Such control sequencing and in-situ remedial actions will rely heavily on accurate source assessments and mass balances for the connecting channels and for whole lakes. The next major steps in the continued recovery of the Great Lakes from toxic chemical contamination will result from the implementation of Remedial Action Plans for the Areas of Concern and from the application of load based controls as part of Lakewide Management Plans. Thus, with the renewed efforts required by the 1987 Great Lakes Water Quality Agreement Protocol, the recovery of the lakes from chemical contamination should continue.

In the 1978 Great Lakes Water Quality Agreement, Canada and the United States called for a virtual elimination of persistent toxins from the Great Lakes with an eventual goal of zero discharge of persistent, toxic organic chemicals. Since 1978, action has taken place at many locations, not the least of which is the Niagara Frontier, the Detroit and St. Clair Rivers, and at many Areas of Concern to reduce or eliminate toxic loads to the Great Lakes. Rather than wait for absolute evidence of a link between toxic chemicals and human health effects, Canada and the United States have acted to proceed toward a toxic free Great Lakes environment.

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This review is based on the work carried out by many individuals from many agencies over a period of many years. We hope that we have thoroughly recognized this by the references in the text and to the figures. In a review of this scope, it is impossible to refer to all of the published work. The bibliography which follows is, however, meant to be comprehensive. The report was completed for March, 1988.

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Appendix 1. Abbreviations

AOC	Area of Concern
CCREM	Canadian Council of Resource and Environmental Ministers
DOE	Environment Canada
FE	Fort Erie
GLWQA	Great Lakes Water Quality Agreement
IJC	International Joint Commission
MISA	Municipal-Industrial Strategy for Abatement
MOE	Ontario Ministry of the Environment
NOTL	Niagara-on-the-Lake
NRC	National Research Council
NRTC	Niagara River Toxics Committee
NYDEC	New York Department of Environmental Conservation
RAP	Remedial Action Plan
RSC	Royal Society of Canada
TSM	Total Suspended Matter
UGLCCS	Upper Great Lakes Connecting Channel Study
USEPA	United States Environmental Protection Agency

Appendix 2. Chemical Abbreviations

*2,3,7,8-TCDD	2,3,7,8-Tetrachlorodibenzo-p-dioxin
*2,3,7,8-TCDF	2,3,7,8-Tetrachlorodibenzofuran
As	**Arsenic**
* **B(a)P**	**Benzo(a)pyrene**
BHCs	**hexachlorocyclohexanes**
α-BHC	**alpha-1,2,3,4,5,6-BHC**
γ-BHC	**gamma-1,2,3,4,5,6-BHC; use Lindane**
CBs	Chlorobenzenes
Cd	**Cadmium**
DCB	Dichlorobenzene
*DDD (TDE)	Dichlorodiphenyl dichloroethane
* **DDE**	**Dichlorodiphenyl dichloroethylene**
* **DDT**	**Dichlorodiphenyl trichloroethane**
* **Dieldrin**	**use for HEOD**
Dioxins	**see PCDD**
* **HCB**	**Hexachlorobenzene**
HCBD	**Hexachlorobutadiene**
HCH	use BHC
HEOD	use Dieldrin
* **Hg**	**Mercury**
* **Mirex**	**Dodecachloropentacyclodecane**
OCS	Octachlorostyrene
OCDD	Octachlorodibenzo-p-dioxin
OCDF	Octachlorodibenzofuran
PAHs	**Polynuclear Aromatic Hydrocarbons**
* **Pb**	**Lead**
* **PCBs**	**Polychlorinated Biphenyls**
PCDD	**Polychlorinated dibenzo-p-dioxin**
PCDF	**Polychlorinated dibenzofuran**
PCP	Pentachlorophenols
PERC	Perchloroethylene; use for Tetrachloroethene
QCB	Pentachlorobenzene
TCB	Trichlorobenzene
TCDD	**use for 2,3,7,8-TCDD**
TCDF	**use for 2,3,7,8-TCDF**
TCP	Trichlorophenol
TeCB	Tetrachlorobenzene
* **Toxaphene**	**use for Chlorinated Bornane**
Zn	Zinc

Bold : Main chemicals discussed in this report.

* : IJC Primary Track Chemicals.

Appendix 3. Glossary

AREA OF CONCERN: a geographic area that fails to meet the General or Specific Objectives of the Agreement where such failure has caused or is likely to cause impairment of beneficial use of of the area's ability to support aquatic life (IJC 1988).

BIOACCUMULATION: general term describing a process by which chemical substances are accumulated by aquatic organisms from water directly or through consumption of food containing the chemicals (CCREM 1987).

BIOASSAY: test used to evaluate the relative potency of a chemical by comparing its effect on a living organism with the effect of a control, without the test chemical, which is run under identical conditions (CCREM 1987).

BIOCONCENTRATION: a process by which there is a net accumulation of a chemical directly from water into aquatic organisms resulting from simultaneous uptake (e.g. by gill or epithelial tissue) and elimination (CCREM 1987).

BIOCONCENTRATION FACTOR (BCF): a unitless value describing the degree to which a chemical can be concentrated in the tissues of an organism in the aquatic environment. At apparent equilibrium during the uptake phase of a bioconcentration test, the BCF is the concentration of a chemical in one or more tissues of the aquatic organisms divided by the average exposure concentration in the test. (CCREM 1987).

BIOMAGNIFICATION: result of the processes of bioconcentration and bioaccumulation by which tissue concentrations of bioaccumulated chemicals increase as the chemical passes up through two or more trophic levels. The term implies an efficient transfer of chemicals from food to consumer, so that residue concentrations increase systematically from one trophic level to the next (CCREM 1987).

BIOTURBATION: the physical disturbance of sediments by burrowing and other activities of organisms (CCREM 1987).

CARCINOGEN: a substance which induces cancer in a living organism (CCREM 1987).

CONGENER: a different configuration or mixture of a specific chemical usually having radical groups attached in numerous potential locations (UGLCCS 1989).

CONTAMINANT: a substance foreign to a natural system or present at unnatural concentrations (UGLCCS 1989).

Appendix 3. Glossary *(Continued)*

DETECTION LIMIT: The smallest concentration or amount of a substance which can be reported as present with a specified degree of certainty by a definite, complete analytical procedure (CCREM 1987).

DIOXIN: a group of approximately 75 chemicals of the chlorinated dibenzodioxin family, including 2,3,7,8-TCDD which is generally considered the most toxic form (UGLCCS 1989).

DREDGING GUIDELINES: procedural directions designed to minimize the adverse effects of shoreline and underwater excavation with primary emphasis on the concentrations of toxic materials within the dredge spoils (UGLCCS 1989).

EFFLUENT: a complex waste material (e.g. liquid industrial discharge or sewage) which may be discharged into the environment (CCREM 1987).

GREAT LAKES WATER QUALITY AGREEMENT: a joint agreement between Canada and the United States which commits the two countries to develop and implement a plan to restore and maintain the many desirable uses of the waters in the Great Lakes Basin. Originally signed in 1978, the Agreement was amended in 1987 (UGLCCS 1989).

GUIDELINE (WATER QUALITY): numerical concentration limit or narrative statement recommended to support and maintain a designated water use (CCREM 1987).

HALF-LIFE: the time require for the concentrations of a substance to diminish to one-half of its original value in a lake or water body (1978 Agreement).

LOADING: the amount of a substance added per unit of lake area per unit time (CCREM 1987).

MASS-BALANCE APPROACH: a management approach in which the aim is to eliminate accumulation of pollutants what will degrade water quality or have adverse affects on living organisms. This approach requires establishment of a mass-balance budget in which the amounts of contaminants entering the system less the quantities stored, transformed, or degraded within the system must equal amounts leaving the system. Application of this approach depends on quantification of sources and effects of contaminants, and mathematical modeling to simulate probable long-term consequences (NRC and RSC 1985).

Appendix 3. Glossary *(Continued)*

MUNICIPAL-INDUSTRIAL STRATEGY FOR ABATEMENT: the principal goal of this program is the virtual elimination of toxics discharged from point sources to surface waters in Ontario (UGLCCS 1989).

MUTAGEN: any substance or effect which alters genetic characteristics or produces an inheritable change in the genetic material (UGLCCS 1989).

NEPHELOID LAYER: regions of turbid bottom water characterized by a maximum in light scattering and particle concentration. Possible sources of nephloid material are eroded shore material, suspended matter brought in a large river, deep sediments eroded by bottom currents and organic matter settling from surface layers (Chambers and Eadie 1981; Sandilands and Mudroch 1983).

NONPOINT SOURCE: source of pollution in which pollutants are discharged over a widespread area or from a number of small inputs rather than from distinct, identifiable sources (UGLCCS 1989).

OBJECTIVE (WATER QUALITY): a numerical concentration limit or narrative statement which has been established to support and protect the designated uses of water at a specified site (CCREM 1987).

OCTANOL-WATER PARTITION COEFFICIENT (POW): the ratio of a chemical's solubility in n-octanol and water at equilibrium. The logarithm of Pow is used as an indication of a chemical's propensity for bioconcentration by aquatic organisms (CCREM 1987).

PERSISTENT TOXIC SUBSTANCE: any toxic substance with a half-life in water of greater than eight weeks (1978 Agreement).

POINT SOURCE: a source of pollution that is distinct and identifiable, such as an outfall pipe from an industrial plant (UGLCCS 1989).

PRIMARY TRACK CHEMICALS: These chemicals are Great Lakes contaminants of known concern, for which abatement and corrective action has been taken, but for which additional measures are required because of their continued presence in the ecosystem at unacceptable levels. They were selected by the IJC. (IJC 1987b)

Appendix 3. Glossary *(Continued)*

RANGE: the difference between the lowest and highest values in a set of data (CCREM 1987).

REMEDIAL ACTION PLAN: this is a plan to be developed with citizen involvement to restore and protect water quality at each of the 42 Areas of Concern in the Great Lakes Basin. The RAP will identify impaired uses, sources of contaminants, desired use goals, target clean-up levels, specific remedial options, schedules for implementation, resource commitments by Michigan and Ontario as well as by the federal governments, municipalities and industries, and monitoring requirements to assess the effectiveness of the remedial options implemented (UGLCCS 1989).

RESUSPENSION: the remixing of sediment particles and pollutants back into the water by storms, currents, organisms and human activities such as dredging (UGLCCS 1989).

SUSPENDED SEDIMENTS/SOLIDS: particulate matter suspended in water (UGLCCS 1989).

TERATOGEN: an agent that increases the incidence of congenital malformations (CCREM 1987).

TOXIC SUBSTANCE: A substance that can cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological or reproductive malfunctions, or physical deformities in any organisms or its offspring or that can become poisonous after concentration in the food chain or in combination with other substances (NRC and RSC 1985).

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An Indexed Bibliography of Toxic Contaminants in Water, Sediments and Biota of the Great Lakes

Part II

R. J. Allan and A. J. Ball[1]

Preface

The main criteria for inclusion of a reference in this bibliography was the discussion of toxic chemical concentrations in the water, suspended solids and/or sediment of the Great Lakes and their connection channels and tributaries. Publications about toxic chemical concentrations in biota were included but to a lesser extent. Some papers dealing specifically with eutrophication, physical properties and processes, analytical techniques, or sampling techniques have also been included.

References

The documents included in this bibliography were journal articles, journal issues, reports, conferences papers and proceedings, dissertations, monographs, chapters, and unpublished manuscripts. The emphasis was on primary sources but some secondary and tertiary publications were also included.

The references are in alphabetical order by first author. For most references, there is a *Notes* section which lists:

1) the testing date(s), which is the year(s) the data was collected. A question mark before the date indicates that a specific date was not given in the text;
2) the number of references or the number of pages of references;
3) the number of tables; and
4) the number of figures.

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Index Terms

The *Index terms* section of each reference lists the headings applied to that publication. These are the same terms used in the Subject Index. Most of the terms included in the Related Subject Headings section were derived from the ASFIS Thesaurus. The Biological Subject Headings section contains lists of both common and scientific names.

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   Notes: 20 ref.; 11 tables; 13 figs.
   Index terms: PCBs/LITERATURE REVIEWS.

2. Allan, R.J. 1982. Dealing with toxic contamination in aquatic ecosystems: The Niagara River — Lake Ontario example. National Water Research Institute Report. 32 pp.
   Notes: 16 figs.
   Index terms: NIAGARA RIVER/LAKE ONTARIO/INDUSTRIAL WASTES/WASTE DISPOSAL SITES/BIOCONCENTRATION/BIOACCUMULATION/Mirex/,3,7,8-TCDD/HCB.

3. Allan, R.J. 1986. The limnological units of the lower Great Lakes - St. Lawrence River corridor and their role in the source and aquatic fate of toxic contaminants. *Water Poll Res Can* 21(2): 168–186.
   Notes: 26 ref.; 18 figs.
   Index terms: LAKE ST. CLAIR/ST. CLAIR RIVER/DETROIT RIVER/LAKE ERIE/NIAGARA RIVER/LAKE ONTARIO/ST. LAWRENCE RIVER/SEDIMENT ANALYSIS/SEDIMENTATION.

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   Notes: 139 refs.
   Part I: 25 tables; 58 figs.
   Part II: 14 tables; 40 figs.
   Index terms: SEDIMENT ANALYSIS/NIAGARA RIVER/LAKE ONTARIO/SORPTION/SUSPENDED PARTICULATE MATTER/Heavy Metals/Pesticide/PCBs.

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Mustela vison/Ring-billed Gulls/*Larus delawarensis*/Snapping Turtle/*Chelydra serpentina*/Spottail Shiners/Notropis hudsonius/White Sucker/*Catostomus commersoni*/Common Goldeneye/*Bucephala clangula*/Waterfowl/Common Loon/*Gavia immer*/Double-crested Cormorant/*Phalacrocorax auritas*/Forster's Tern/*Sterna forsteri*/ Great Horned Owl/*Bubo virginianus*/Great Blue Heron/*Ardea herodias*/Black Duck/*Anas rupripes*/Mammals/Muskrat/*Ondatra zibethica*/Osprey/*Pandion haliaetus*/Canadian Otter/*Lutra canadensis*/Channel Catfish/*Ictalurus punctatus*.

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Notes: Testing date: 1983; 18 ref.; 9 tables; 5 figs.
Index terms: DETROIT RIVER/WATER COLUMN/SEDIMENT ANALYSIS/SUSPENDED PARTICULATE MATTER/DCB/TCB/TeCB/PCBs/Toxaphene/PAHs/Chlorophenols/QCB/HCB/HCBD/OCS/DDT/Mirex/Chlordane/a-BHC/Heptachlor epoxide/Heptachlor/Endosulfan/Dieldrin/Endrin/Methoxychlor/B(a)P.

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Notes: Testing dates: 1980–1981; 16 ref.; 4 tables
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Notes: Testing dates: 1960s–1970s; 36 ref.; 94 figs.
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Index terms: WATER COLUMN/Arsenic/Radium Isotopes/Nitrates/LAKE ONTARIO/INDUSTRIAL WASTES/NUCLEAR POWER PLANTS.

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Notes: Testing date: 1978; 5 ref.; 3 tables; 2 figs.
Index terms: WATER COLUMN/Cesium Isotopes/Radium Isotopes/Beryllium Isotopes/Zirconium Isotopes/Ruthenium Isotopes/Antimony Isotopes/Cerium Isotopes/Thorium Isotopes/LAKE ONTARIO/WATER TREATMENT PLANTS.

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Index terms: Benthos/*Stylodrilus heringianus*/Mayfly/SEDIMENT ANALYSIS/BIOTURBATION/*Pontoporeia hoya*/BIOACCUMULATION/SEDIMENT-WATER INTERFACE/LITERATURE REVIEWS/PCBs/PAHs/B(a)P/HCB/Heavy metals/LAKE ERIE/LAKE MICHIGAN/LAKE ONTARIO.

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Index terms: SUSPENDED PARTICULATE MATTER/ Amphipods/Oligochaetes/SEDIMENT ANALYSIS/Bloater Chubs/ *Coregonus hoyi*/Radionuclides/Lead Isotopes/Beryllium Isotopes/ Cesium Isotopes/B(a)P/PAHs/DDT/PCBs/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/BIOTURBATION/ SEDIMENT-WATER INTERFACE/SEASONAL VARIATIONS/ MATHEMATICAL MODELS/LITERATURE REVIEWS.

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Notes: Testing dates: 1975–1976; 35 ref.; 4 tables; 4 figs.
Index terms: ATMOSPHERIC PRECIPITATIONS/Heavy Metals/ Aluminum/Iron/Manganese/Zinc/Copper/Lead/Cadmium/Cobalt/ LAKE MICHIGAN.

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Index terms: AEROSOLS/SURFACE FILMS/AIR-WATER INTERFACE/ATMOSPHERIC PRECIPITATIONS/Heavy Metals/Sulphates/PCBs/DDT/a-BHC/Dieldrin/HCB/Methoxychlor/ Endosulfan/PAHs/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/Iron/Manganese/ Lead/Chromium/Zinc/Cadmium/Nickel/Copper.

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Notes: 145 ref.; 12 tables; 22 figs.
Index terms: PCBs/LAKE SUPERIOR/ATMOSPHERIC PRECIPITATIONS/AIR TRANSPORTATION/AIR-WATER INTERFACE/AIR-WATER EXCHANGES/LITERATURE REVIEWS/MASS BALANCE APPROACH.

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Notes: Testing dates: 1977–1978; 76 ref.; 5 tables; 10 figs.
Index terms: LAKE SUPERIOR/PCBs/ATMOSPHERIC PRECIPITATIONS/SEDIMENT ANALYSIS/DDE/MASS BALANCE APPROACH/WATER COLUMN/SUSPENDED PARTICULATE MATTER/SISKIWIT LAKE.

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Notes: Testing dates: 1978–1980; 34 ref.; 2 tables; 1 fig.
Index terms: PCBs/LAKE SUPERIOR/ATMOSPHERIC PRECIPITATIONS/AEROSOLS.

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Notes: 199 ref.; 36 tables; 1 fig.
Index terms: ATMOSPHERIC PRECIPITATIONS/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/ATMOSPHERIC CIRCULATION/PCBs/DDT/a-BHC/Endosulfan/Methoxychlor/PAHs/Phthalate Esters.

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Index terms: Mirex/Waterfowl/Fish/Mammals/BIOACCUMULATION/LITERATURE REVIEWS/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR.

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Index terms: PAHs/LITERATURE REVIEWS.

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Notes: 10 pages of references; 7 tables
Index terms: Arsenic/Fish/Birds/Mammals/Humans/Aquatic Insects/Crustaceans/Mollusks/Phytoplankton/SEDIMENT ANALYSIS/WATER COLUMN/LITERATURE REVIEWS.

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Notes: 4 pages of references; 7 tables
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Index terms: NIAGARA RIVER/TEMPORAL VARIATIONS/Phosphorus/Nitrates/WATER COLUMN.

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RIVER/MUSKEGON RIVER/SAGINAW BAY/SAGINAW RIVER/ROUGE RIVER, MI/MAUMEE RIVER/RAISON RIVER/ ST. MARYS RIVER/MAGNETAWAN RIVER/SAUGEEN RIVER/ SANDUSKY RIVER/GRAND RIVER, ON/ASHTABULA RIVER/ TRENT RIVER/DON RIVER/HUMBER RIVER/CREDIT RIVER/GENESEE RIVER/OSWEGO RIVER.

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Toxaphene/OCS/PBBs/Endosulfan/Heptachlor epoxide/LAKE HURON/Aldrin/Arsenic/Barium/Boron/Cadmium.

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NON-POINT SOURCES/Pesticide/SEDIMENT ANALYSIS/ WASTE DISPOSAL SITES/ATMOSPHERIC PRECIPITATIONS/ AGRICULTURAL RUNOFF/DOMESTIC WASTES/PCBs/Lead/ DDT/Aldrin/Dieldrin/Chlordane/Heptachlor/Heptachlor epoxide/ Atrazine/HCB/Mirex/Mercury.

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mordax/Walleye/*Stizostedion vitreum*/Herring Gull/*Larus argentatus*/Eggs/TEMPORAL VARIATIONS/Double-crested Cormorant/*Phalacrocorax auritas*/DDT/PAHs/Chlorobenzenes/HCB/Mirex/DDE/Waterfowl/Brown Bullhead/*Ictalurus nebulosus*/White Sucker/*Catostomus commersoni*/Lindane/a-BHC/Radionuclides/Arsenic.

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Index terms: INDUSTRIAL WASTES/WASTE DISPOSAL SITES/NIAGARA RIVER/SEDIMENT ANALYSIS/BERGHOLTZ CREEK/Chlorobenzenes/DCB/TCB/TeCB/QCB/HCB/Chlorotoluenes/a-BHC/Mirex.

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Index terms: LAKE ONTARIO/NIAGARA RIVER/BUFFALO RIVER/TWELVE MILE CREEK, NY/EIGHTEEN MILE CREEK/GENESEE RIVER/OSWEGO RIVER/ST. LAWRENCE RIVER/BLACK RIVER, NY/a-BHC/Lindane/Dacthal/Heptachlor epoxide/Chlordane/Endosulfan/Dieldrin/Mirex/DDE/DDD/TCB/HCB/OCS/PCBs/Fish/BERGHOLTZ CREEK.

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Notes: Testing dates: 1982–1984; 24 ref.; 4 tables; 9 figs.
Index terms: Fish/SEDIMENT ANALYSIS/BUFFALO RIVER/TWELVE MILE CREEK, NY/EIGHTEEN MILE CREEK/GENESEE RIVER/OSWEGO RIVER/BLACK RIVER, NY/ST. LAWRENCE RIVER/BERGHOLTZ CREEK/PCBs.

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Notes: Testing date: 1983; 26 ref.; 2 tables; 1 fig.
Index terms: Fish/AU SABLE RIVER, MI/SAGINAW BAY/SAGINAW RIVER/TITTABAWASSEE RIVER/ST. MARYS RIVER/LAKE SUPERIOR/LAKE HURON/TeCB/Mono-cyclic aromatics/a-BHC/HCB/Heptachlor epoxide/Chlordane/Dieldrin/DDE/DDD/DDT/PCBs/OCS/PBBs/Dacthal.

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Index terms: ST. LAWRENCE RIVER/SEDIMENT ANALYSIS/Nickel/Cobalt/Chromium/Vanadium/Lead/Zinc/Mercury/Arsenic/HCB/DDE/PCBs.

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Notes: 33 ref.
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Notes: Testing date: 1982; 27 ref.; 1 table; 4 figs.
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Index terms: WELLAND RIVER/NIAGARA RIVER/Halogenated aliphatic hydrocarbons/WATER COLUMN.

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Notes: Testing date: 1984; 20 ref.; 1 table; 9 figs.
Index terms: ST. CLAIR RIVER/LAKE ST. CLAIR/Volatile halogenated aliphatic hydrocarbons/RIVER PLUMES/WATER COLUMN/TEMPERATURE CHARTS.

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Notes: Testing date: 1985; 4 ref.; 2 tables; 7 figs.
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Notes: Testing date: 1981; 19 ref.; 2 tables; 7 figs.
Index terms: LAKE ONTARIO/NIAGARA RIVER/WATER COLUMN/Volatile halogenated aliphatic hydrocarbons/WELLAND CANAL/BLACK RIVER, NY/HUMBER RIVER/DON RIVER/ROUGE RIVER, ON/POINT SOURCES.

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Index terms: BENTHOS/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/BIOACCUMULATION/BIOTURBATION/Amphipods/*Pontoporeia hoya*/ Freshwater shrimp/Mysis relicta/Mayfly/*Hexagenia*/Oligochaetes/ PCBs/DDE/DDD/Dieldrin/Chlordane/HCB/OCS/B(a)P/PAHs/ LITERATURE REVIEWS.

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Index terms: BIOACCUMULATION/PCBs/LAKE ONTARIO/CHEMICAL SPECIATION/WATER COLUMN/SUSPENDED PARTICULATE MATTER/SEDIMENT ANALYSIS/Phytoplankton/Amphipods/Oligochaetes/Alewife/*Alosa pseudoharengus*/Slimy Sculpin/*Cottus cognatus*/Rainbow Smelt/*Osmerus mordax*/Coho Salmon/*Oncorhynchus kisutch*/Rainbow Trout/*Salmo gairdneri*/Lake Trout/*Salvelinus namaycush*/Mysid/*Mysis relicta*/DDD/DDE/DDT/Mirex/Chlordane/a-BHC/Lindane/HCBD/OCS/HCB/QCB/TeCB/TCB/Chlorotoluenes/Chlorobenzenes.

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Index terms: LAKE MICHIGAN/LAKE ERIE/WATER COLUMN/SEDIMENT ANALYSIS/LITERATURE REVIEWS/Cadmium/Copper/Lead/Mercury/Zinc/PCBs/DDT/Dieldrin/Endrin/Toxaphene/Chlordane/Phthalate Esters/Fathead Minnow.

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Index terms: Herring Gull/*Larus argentatus*/PCDD/Eggs/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/,3,7,8-TCDD.

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Index terms: Mercury/Eggs/Birds/LAKE ST. CLAIR/Mallard/*Anas platyrhynchos*/Common Tern/*Sterna hirundo*/Black-crowned Night Heron/*Nycticorax nycticorax*/Great Egret/*Casmerodius albus*.

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Index terms: MATHEMATICAL MODELS/Chlorobenzenes/RIVER PLUMES/NIAGARA RIVER/LAKE ONTARIO/SUSPENDED PARTICULATE MATTER/LAKE CURRENTS/TCB/TeCB/SORPTION/WATER COLUMN.

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Index terms: LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/Phytoplankton/LITERATURE REVIEWS.

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Notes: Testing date: 1976–1978; 15 ref.; 6 tables
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Notes: Testing dates: 1981–1982; 29 ref.; 2 tables
Index terms: Brain/Great Horned Owl/*Bubo virginianus*/DDE/Dieldrin/Mirex/HCB/PCBs/Heptachlor epoxide/OCS/LAKE ONTARIO.

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Index terms: LAKE SUPERIOR/ATMOSPHERIC PRECIPITATIONS/a-BHC/Lindane/Heptachlor epoxide/Dieldrin/Endrin/DDT/Methoxychlor/PCBs/HCB/Chlordane/Mirex/Toxaphene/DDD/DDE.

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Notes: Testing dates: 1970s; 54 ref.; 3 tables
Index terms: LAKE ONTARIO/DDT/Mirex/PCBs/Dieldrin/Aldrin/Lindane/a-BHC/Chlorobenzenes/Toxaphene/,3,7,8-TCDD/Volatile halogenated aliphatic hydrocarbons/Fish/WATER COLUMN/LITERATURE REVIEWS.

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Index terms: ATMOSPHERIC PRECIPITATIONS/LAKE ERIE/LAKE HURON/LAKE ONTARIO/LAKE SUPERIOR/PCBs/Lindane/a-BHC/DDT/Endosulfan/Dieldrin/Methoxychlor/HCB.

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Notes: Testing dates: 1976–1977; 10 ref.; 4 tables; 2 fig.
Index terms: LAKE ERIE/LAKE HURON/LAKE ONTARIO/LAKE SUPERIOR/ATMOSPHERIC PRECIPITATIONS/PCBs/Lindane/a-BHC/DDT/Endosulfan/Dieldrin/Methoxychlor.

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Notes: 10 chapters
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Notes: Testing date: 1983; 64 ref.; 7 tables; 1 fig.
Index terms: Herring Gull/*Larus argentatus*/LAKE ERIE/LAKE HURON/LAKE ONTARIO/LAKE SUPERIOR/Liver/Kidneys/Bones/Aluminum/Cadmium/Chromium/Copper/Iron/Mercury/Manganese/Phosphorus/Lead/Strontium/Zinc/HAMILTON HARBOUR.

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Index terms: Caspian Tern/Eggs/LAKE ERIE/LAKE HURON/LAKE MICHIGAN/LAKE ONTARIO/LAKE SUPERIOR/*Sterna caspia*.

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RADIUM ISOTOPES 147 148 149 348 352 604 605 719 771

RADON ISOTOPES 605

RAINBOW SMELT 285 290 337 528 529 559 579 659 766 793

RAINBOW TROUT 20 131 413 487 528 529 530 531 533 548 551 578 579 600

RAISON RIVER 153 211

REDHORSE SUCKER 51 671 804

RING-BILLED GULLS 55 109 252 292 297 430 547 660 662 681

RIVER PLUMES 10 78 111 112 217 360 570 705

ROCK BASS 138 209 429 659 671

ROUGE RIVER, MI 112 211 275 363 439 462

ROUGE RIVER, ON 226 232 362

ROUND WHITEFISH 493

RUBIDIUM ISOTOPES 146 639

RUTHENIUM ISOTOPES 149 350 719

SAGINAW BAY 10 58 81 90 127 131 189 190 191 206 211 260 268 317 343 429 489 493 636 663 672 722 745 780 803

SAGINAW RIVER 211 343 780

SAGUENAY RIVER 123 420 428 598 719

Salmo gairdneri 20 131 413 487 528 529 530 531 533 548 551 578 579 600

Salmo trutta 20 97 131 429 528 529 531 533 551 700

SALMONIDS 45 499 550

Salvelinus namaycush 20 109 131 141 262 285 337 429 444 447 528 529 531 533 551 575 579 591 600 633 646 671 699 700 702 737 739 743 766 793

Salvelinus tontinalis 702

SANDUSKY RIVER 211

SAUGEEN RIVER 48 211 221 224 226 232 499 584

SEA LAMPREY 357 368

SEASONAL VARIATIONS 92 93 158 226 242 400 407 443 444 483 507 542 543 756

SEDIMENT ANALYSIS 3 4 6 10 14 15 19 22 30 32 38 48 51 53 61 64 71 72 92 95 96 97 99 104 106 113 115 116 127 128 129 130 133 135 143 148 151 152 153 155 156 157 158 159 165 167 182 187 188 195 196 197 199 200 202 204 205 211 218 219 222 227 228 229 230 231 233 239 260 261 264 271 275 279 294 297 299 300 303 306 316 317 318 320 328 330 331 333 334 337 339 340 342 344 349 350 351 352 356 366 371 372 373 378 379 380 381 386 389 390 394 398 399 402 405 411 418 420 425 427 428 436 439 440 444 446 448 452 457 459 462 463 464 465 468 475 476 477 483 486 487 489 490 506 508 509 510 511 512 513 514 515 516 517

518 521 522 523 534 535 536 539 561 562 563 566 567 568 570 571 572 573 575 579 580 585 586 587 588 590 592 598 599 606 613 614 615 620 621 625 629 633 639 643 647 653 656 682 686 687 688 689 690 694 706 719 725 732 734 736 744 746 747 748 749 750 752 753 754 755 758 763 764 766 767 772 788

SEDIMENT DISTRIBUTION 10 93 599 601 716

SEDIMENT TRANSPORT 329 334 338 410 615 688

SEDIMENT-WATER INTERFACE 9 32 83 154 156 158 338 541 666

SEDIMENTATION 3 9 10 32 48 90 334 540 563 566

SELENIUM 63 71 72 76 84 101 175 200 205 259 276 299 399 418 429 468 474 562 625 649 650 651 652 654 672 678 706 719 755 758 793

SELENIUM ISOTOPES 146

SEWAGE TREATMENT PLANTS 63 112 146 405 467 599

SHEBOYGAN RIVER 65 81 103 131 134 138 139 211 293 429 445 590 671

SILVER 12 63 71 72 76 106 121 205 211 542 649 651 652 654 678 754

SISKIWIT LAKE 22 128 129 130 167 262 264 483 735 736 737

SLIMY SCULPIN 579

SMALLMOUTH BASS 20 96 421 429 528 529 533 548

SMELTS 658

SNAPPING TURTLE 70 109 117 657 710

SORPTION 4 9 10 32 111 159 192 540 566 568 705

SPANISH RIVER 48 584

SPOTTAIL SHINERS 109 196 337 398 728 729 730 731

ST. CLAIR RIVER 3 10 48 79 86 87 94 97 98 102 114 135 197 198 199 209 211 226 232 265 267 296 317 320 324 330 331 337 360 361 374 376 384 410 411 412 457 462 466 467 468 477 513 534 569 571 574 580 581 582 620 621 626 641 647 656 685 707 729 730 762 763 764 767 777 782

ST. JOSEPH RIVER 65 75 103 211 518 648

ST. LAWRENCE RIVER 3 8 10 20 42 48 55 84 96 98 110 116 123 124 320 324 326 330 331 337 341 342 344 364 365 366 399 404 420 428 429 436 437 440 441 442 468 469 471 473 479 486 514 528 529 533 581 582 584 585 586 587 592 603 671 673 674 686 710 719 730 741

ST. LOUIS RIVER 166 258 318

ST. MARYS RIVER 10 48 145 166 211 232 260 265 296 298 317 320 324 330 331 337 343 376 467 581 582 584 626 730 763 764 777 782

Sterna caspia 721 780

Sterna forsteri 109 292 302 392 393 700 777

Sterna hirundo 56 109 121 125 242 252 253 292 503 547 704 778

Stizostedion vitreum 20 97 131 138 209 285 337 429 591 600 671 699 700 702

STRONTIUM 72 651 652 654 687 720

STRONTIUM ISOTOPES 150

Stylodrilus heringianus 156 220 390 615 640

SUCKERS 285

SULPHATES 12 161 488 585

SURFACE FILMS 97 161 219 363 458 589 606 634

SUSPENDED PARTICULATE MATTER 4 10 22 30 31 32 33 48 63 77 82 83 87 92 93 95 104 110 115 123 148 152 157 158 159 167 192 195 196 200 218 232 266 271 316 317 318 331 334 337 363 364 373 396 398 411 436 437 440 443 452 458 479 486 491 501 505 507 510 546 562 563 566 569 572 573 574 579 582 585 592 606 615 634 636 649 650 651 652 654 663 666 672 688 705 716 719 740 744 750 751 763 764 769 770

TAWAS RIVER 648

TCB 10 46 61 63 76 78 86 115 151 198 199 200 217 218 272 334 339 341 366 372 402 411 444 460 461 468 544 566 567 568 569 570 571 572 573 575 576 578 579 580 588 705 706 707 722 740

TECB 10 61 63 76 78 79 103 115 151 198 200 217 218 272 334 339 343 366 372 402 411 460 461 468 544 566 567 568 569 570 571 572 573 575 576 578 579 580 588 606 705 706 707 722 740 777

TEMPERATURE CHARTS 62 144 280 345 360 688

TEMPORAL DISTRIBUTION 274 422

TEMPORAL VARIATIONS 10 13 44 62 88 139 144 150 186 230 261 296 316 317 318 337 389 397 400 423 456 532 537 625 633 667 674 706 708 728 741 746 751 783

THALLIUM 76 126

THAMES RIVER 48 224 226 584

THORIUM ISOTOPES 146 149 605 719

TIN 639

TITTABAWASSEE RIVER 206 268 343 406

TOLUENE 76 114

TOXAPHENE 10 65 76 100 103 115 122 131 139 184 238 262 276 286 292 293 316 317 318 370 376 389 531 562 565 584 591 619 624 633 635 671 683 694 713 715 716 724 735 795

TRENT RIVER 48 211 219 226 232 405 584

TRIFLURALIN 221

Tubifex tubifex 567 615 640

TWELVE MILE CREEK, NY 341 342

TWELVE MILE CREEK, ON 48 113 226 405 438 706

URANIUM ISOTOPES 604 605 719 771

VANADIUM 12 71 72 344 380 428 514 625 649 650 651 652 654 748 754

VOLATILE ALIPHATIC HYDROCARBONS 113 114 200 369

VOLATILE HALOGENATED ALIPHATIC HYDROCARBONS 8 10 112 113 200 360 361 362 441 715

WALLEYE 20 97 131 138 209 285 337 429 591 600 671 699 700 702

WALLEYE PIKE 51

WASTE DISPOSAL SITES 2 107 265 320 339 405 689

WATER COLUMN 10 14 32 33 34 46 48 63 76 77 84 85 87 95 97 104 110 111 112 113 114 115 116 133 143 144 147 149 150 152 159 164 167 182 185 186 187 188 195 196 197 198 199 200 207 208 218 219 224 258 260 263 266 270 279 300 316 317 318 320 323 324 328 330 331 333 334 337 348 359 360 361 362 363 364 365 367 369 373 374 385 389 395 396 398 402 404 405 406 411 422 436 437 438 440 441 443 447 452 457 458 459 460 461 462 468 477 478 479 480 505 518 541 542 543 544 545 546 562 566 569 572 574 575 576 577 579 585 589 592 605 606 608 609 613 614 625 631 634 643 646 649 650 651 652 654 682 683 690 694 705 706 707 715 716 719 724 733 737 740 744 751 758 763 764 766 805

WATER TRANSPARENCY 83 92 408 625 666 667

WATER TREATMENT PLANTS 149 599

WATERFOWL 109 174 178 216 286 292 300 337 382 383 432 433 594 596 643 706 777 784

WAUKEGAN HARBOR 306 734

WELLAND CANAL 111 113 226 232 362 405 438 658

WELLAND RIVER 113 142 359 438 584 706

WHITE BASS 209 548

WHITE CRAPPIE 306

WHITE PERCH 20 285 528 529 533 658 659

WHITE SUCKER 20 51 74 96 97 109 138 287 306 337 354 421 429 528 548 658 659 804

WHITEFISH 131 285 357 429 671 699 735 766

WOLF RIVER 131 138

YELLOW BULLHEAD 138

YELLOW PERCH 20 29 97 131 219 285 306 354 429 548 658 659 671 672

ZINC 12 14 63 71 72 76 84 99 101 106 113 116 121 123 160 161 187 195 196 200 205 211 235 275 279 286 332 334 344 373 379 380 381 385 397 398 399 400 401 428 429 438 439 440 443 463 467 468 475 480 488 506 508 509 510 511 512 514 515 516 521 522 542 561 563 585 586 587 589 598 599 613 614 615 624 625 639 643 649 650 651 652 653 654 663 666 669 672 678 680 683 687 694 706 719 720 741 751 754 755 756

ZINC ISOTOPE 350

ZIRCONIUM 72 510

ZIRCONIUM ISOTOPES 146 149

ZOOPLANKTON 59 195 202 210 234 290 299 312 316 317 318 325 327 337 347 481 482 642 643 667 682 706 766 791

Geographical Subject Headings

Ashtabula River
Au Sable River, MI
Au Sable River, ON
Bay of Quinte
Bergholtz Creek
Black River, NY
Black River, OH
Black River, ON
Buffalo River
Chequamegon River
Clinton River
Credit River
Cuyahoga River
Detroit River
Don River
Ecorse River
Eighteen Mile Creek
Escanaba River
Fox River
French River
Genesee River
Georgian Bay
Grand River, MI
Grand River, ON
Green Bay
Hamilton Harbour
Humber River
Kalamazoo River
Kinnickinnic River
Lake Erie
Lake Huron
Lake Michigan
Lake Ontario
Lake St. Clair
Lake Superior
Little Manistee River
Magnetawan River
Manistee River
Manistique River
Maumee River
Menominee River
Milwaukee River
Muskegon River
Niagara River
Nipigon River
Oswego River
Platt River
Raison River
Rouge River, MI
Rouge River, ON
Saginaw Bay
Saginaw River
Saguenay River
Sandusky River
Saugeen River
Sheboygan River
Siskiwit Lake
Spanish River
St. Clair River
St. Joseph River
St. Lawrence River
St. Louis River
St. Marys River
Tawas River
Thames River
Tittabawassee River
Trent River
Twelve Mile Creek, NY
Twelve Mile Creek, ON
Waukegan Harbor
Welland Canal
Welland River
Wolf River

Chemical Subject Headings

2,3,7,8-TCDD — 2,3,7,8-Tetrachlorodibenzo-p-dioxin
2,3,7,8-TCDF — 2,3,7,8-Tetrachlorodibenzofuran
Aldrin
Alkylated Lead
Alkylated Tins
Aluminum
Americium Isotope
Anthracene — PAHs
Antimony
Antimony Isotopes
Arsenic
Atrazine
B(a)P — Benzo(a)pyrene, PAHs
Barium
Benzene
Beryllium
Beryllium Isotopes
a-BHC — alpha-BHC
BHC — Hexachlorocyclohexane — use for HCH
Bismuth
Bismuth Isotope
Boron
Butyltin — use Alkylated Tins
Cadmium
Cerium Isotopes
Cesium Isotopes
Chlordane
Chlorinated Bornane — use Toxaphene
Chlorobenzenes
Chlorophenols
Chlorostyrenes
Chlorotoluenes
Chromium
Chromium Isotopes
Cobalt
Cobalt Isotope
Copper
Curium Isotopes
Dacthal — Tetrachloroterephthalate
DCB — Dichlorobenzene
DDD — Dichlorodiphenyl dichloroethane, use for TDE
DDE — Dichlorodiphenyl dichloroethylene
DDT — Dichlorodiphenyl trichloroethane

Dieldrin — use for HEOD
Dissolved Oxygen
Endosulfans
Endrin
Europium Isotope
Halogenated aliphatic hydrocarbons
HCB — Hexachlorobenzene
HCBD — Hexachlorobutadiene
HCH — Hexachlorocyclohexane — use BHC
Heavy Metals
HEOD — use Dieldrin
Heptachlor epoxide
Heptachlor
Iodine Isotopes
Iron
Kepone — Mirex
Lead
Lead Isotopes
Lithium
Lindane -- use for gamma-BHC
Manganese
Manganese Isotope
Mercury
Methoxychlor
MFO — Mixed Function Oxydase
Mirex
Molybdenum
Mono-cyclic aromatics
Neptunium Isotopes
Nickel
Niobium Isotopes
Nitrates
Norachlor
OCS — Octachlorostyrene
Organotin
PAHs — Polynuclear Aromatic Hydrocarbons
PBB — Polybrominated Biphenyls
PCBs — Polychlorinated Biphenyls
PCDD — Polychlorinated dibenzo-p-dioxin
PCDF — Polychlorinated dibenzofuran
PCS — Polychlorinated Styrenes
PERC — Perchloroethylene — use for Tetrachloroethene
Pesticide
Petroleum Hydrocarbons
Phenol

Phosphorus
Phthalate Esters
Polonium Isotopes
Protactinium Isotopes
QCB — Pentachlorobenzene
QSAR — Quantitative Structure-Activity Correlations
Radionuclides
Radium Isotopes
Radon Isotopes
Rubidium Isotopes
Ruthenium Isotopes
Selenium
Selenium Isotopes
Silver
Strontium
Strontium Isotopes
Sulphates
TCB — Trichlorobenzene
TDE — use DDD
TeCB — Tetrachlorobenzene
Thallium
Thorium Isotopes
Toluene
Toxaphene — use for Chlorinated Bornane
Trifluralin — Treflan
Uranium Isotopes
Vanadium
Volatile aliphatic hydrocarbons
Volatile halogenated aliphatic hydrocarbons
Zinc
Zinc Isotope
Zirconium
Zirconium Isotopes

Biologic Subject Headings

1. Body Parts

Bones
Brain
Eggs
Gills
Kidneys
Lipids
Liver
Muscle

2. Common Names

Alewife — *Alosa pseudoharengus*
Amphipods
Amphipods — *Hyalella azteca*
Amphipods — *Pontoporeia affinis*
Amphipods — *Pontoporeia hoya*
Aquatic Insects
Bacteria
Bald eagle — *Haliaeetus leucocephalus*
Bass — *Micropterus* spp.
Belted Kingfisher — *Ceryle alcyon*
Beluga Whales — *Delphinapterus leucas*, use for White Whales
Birds
Black Bullhead — *Ictalurus melas*
Black Crappie — *Poxomis negromaculatus*
Black Duck — *Anas rupripes*
Black-Backed Gull
Black-crowned Night Heron — *Nycticorax nycticorax*
Bloater Chubs — *Coregonus hoyi*
Bluegill — *Lepomis macrochirus*
Brook Trout — *Salvelinus tontinalis*
Brown Bullhead — *Ictalurus nebulosus*
Brown Trout — *Salmo trutta*
Canadian Otter — *Lutra candensis*
Carp — *Cyprinus carpio*
Carp Goldfish Hybrid
Caspian Tern — *Sterna caspia*
Cattle Egret — *Bubulcus ibis*
Channel Catfish — *Ictalurus punctatus*
Chinook Salmon — *Oncorhynchus tshawytscha*
Chironomids
Coho Salmon — *Oncorhynchus kisutch*

Common Goldeneye — *Bucephala clangula*
Common Loon — *Gavia immer*
Common Tern — *Sterna hirundo*
Crustaceans
Double-crested Cormorant — *Phalacrocorax auritas*
Ducks — use Waterfowl
Earthworms
Eels
Fathead Minnow — *Pimephales promelas*
Fish
Forster's Tern — *Sterna forsteri*
Freshwater Clam — *Elliptio complanata*
Freshwater Drum — *Aplodinotes grunniens*
Freshwater shrimp — *Mysis relicta*
Golden Shiner — *Notemigonus crysoleucas*
Goldfish — *Carassius auratus*
Great Blue Heron — *Ardea herodias*
Great Egret — *Casmerodius albus*
Great Horned Owl — *Bubo virginianus*
Greater Scaup — *Aythya marila*
Green-back Heron — *Butorides striatus*
Herons
Herring Gull — *Larus argentatus*
Humans
Lake Trout — *Salvelinus namaycush*
Lesser Scaup — *Aythya affinis*
Little Gull — *Larus minutus*
Longnose Sucker — *Catostomus catostomus*
Mallard — *Anas platyrhynchos*
Mammals
Mayfly — *Hexagenia*
Mink — *Mustela vison*
Mollusks
Muskellunge — *Esox masquinongy*
Muskrat — *Ondatra zibethica*
Mysid — *Mysis relicta*
Northern Longnose Gar — *Lepistostcus osseus*
Northern Pike — *Esox lucius*
Oligochaetes — *Limnodrilus hoffmeisteri*
Oligochaetes — *Stylodrilus heringianus*
Oligochaetes — *Tubifex tubifex*
Osprey — *Pandion haliaetus*
Otter — see also Canadian Otter
Peregrine Falcon — *Falco peregrinus*
Phytoplankton

Polychaetes
Pumpkin Seed — *Lepomis gibbosus*
Rainbow Smelt — *Osmerus mordax*
Rainbow Trout — *Salmo gairdneri*
Redhorse Sucker — *Moxostoma erythruran*
Ring-billed Gulls — *Larus delawarensis*
River Redhorse — *Moxostoma carinatum*
Rock Bass — *Amploplites rupestris*
Round Whitefish — *Prosopium cylindraceum*
Salmonids
Sea Lamprey — *Petromyzon marinus*
Slimy Sculpin — *Cottus cognatus*
Smallmouth Bass — *Micropterus dolomieui*
Smelts — *Osmeridae*
Snapping Turtle — *Chelydra serpentina*
Spottail Shiners — *Notropis hudsonius*
Suckers — *Catostomus* spp.
Walleye — *Stizostedion vitreum*
Walleye Pike
Waterfowl — use for Ducks
White Bass — *Morone chrysops*
White Crappie — *Poximis annularis*
White Perch
White Sucker — *Catostomus commersoni*
White Whale — use Beluga Whale
Whitefish — *Coregonus culpeaformis*
Yellow Bullhead — *Ictalurus natalis*
Yellow Perch — *Perca falvescens*
Zooplankton

3. Scientific Names

Alosa pseudoharengus — Alewife
Amploplites rupestris — Rock Bass
Anas platyrhynchos — Mallard
Anas rupripes — Black Duck
Aplodinotes grunniens — Freshwater Drum
Ardea herodias — Great Blue Heron
Aythya affinis — Lesser Scaup
Aythya marila — Greater Scaup
Bubo virginianus — Great Horned Owl
Bubulcus ibis — Cattle Egret
Bucephala clangula — Common Goldeneye
Butorides striatus — Green-back Heron
Carassius auratus — Goldfish

Casmerodius albus — Great Egret
Catostomus spp. — Suckers
Catostomus catostomus — Longnose Sucker
Catostomus commersoni — White Sucker
Chelydra serpentina — Snapping Turtle
Coregonus culpeaformis — Whitefish
Coregonus hoyi — Bloater Chubs
Cottus cognatus — Slimy Sculpin
Cyprinus carpio — Carp
Daphnia magna
Delphinapterus leucas — Beluga or White Whales
Elliptio complanata — Freshwater Clam
Esox lucius — Northern Pike
Esox masquinongy — Muskellunge
Falco eregrinus — Peregrine Falcon
Gavia immer — Common Loon
Haliaeetus leucocephalus — Bald eagle
Hexagenia spp. — Mayfly
Hyalella azteca — Amphipods
Ictalurus melas — Black Bullhead
Ictalurus natalis — Yellow Bullhead
Ictalurus nebulosus — Brown Bullhead
Ictalurus punctatus — Channel Catfish
Larus argentatus — Herring Gull
Larus delawarensis — Ring-billed Gulls
Larus minutus — Little Gull
Lepistostcus osseus — Northern Longnose Gar
Lepomis gibbosus — Pumpkin Seed
Lepomis macrochirus — Bluegill
Limnodrilus hoffmeisteri — Oligochaetes
Lutra candensis — Canadian Otter
Micropterus dolomieui — Smallmouth Bass
Micropterus spp. — Bass
Morone chrysops — White Bass
Moxostoma erythruran — Redhorse Sucker
Mustela vison — Mink
Mysis relicta — Freshwater shrimp, Mysid
Notemigonus crysoleucas — Golden Shiner
Notropis hudsonius — Spottail Shiners
Nycticorax nycticorax — Black-crowned Night Heron
Oncorhynchus kisutch — Coho Salmon
Oncorhynchus tshawytscha — Chinook Salmon
Ondatra zibethica — Muskrat
Osmerus mordax — Rainbow Smelt
Pandion haliaetus — Osprey

Perca falvescens — Yellow Perch
Petromyzon marinus — Sea Lamprey
Phalacrocorax auritas — Double-crested Cormorant
Pimephales promelas — Fathead Minnow
Pontoporeia affinis — Amphipods
Pontoporeia hoya — Amphipods
Poximis annularis — White Crappie
Poxomis negromaculatus — Black Crappie
Prosopium cylindraceum — Round Whitefish
Salmo gairdneri — Rainbow Trout
Salmo trutta — Brown Trout
Salvelinus namaycush — Lake Trout
Salvelinus namaycush siscowet — Lake Trout
Salvelinus tontinalis — Brook Trout
Sterna caspia — Caspian Tern
Sterna forsteri — Forster's Tern
Sterno hirundo — Common Tern
Stizostedion vitreum — Walleye
Stylodrilus heringianus — Oligochaetes
Tubifex tubifex — Oligochaetes

Related Subject Headings

AEROSOLS
AGRICULTURAL RUNOFF
AIR TRANSPORTATION
AIR-WATER EXCHANGES
AIR-WATER INTERFACE
ATMOSPHERIC CHEMISTRY
ATMOSPHERIC CIRCULATION
ATMOSPHERIC PARTICULATES
ATMOSPHERIC PRECIPITATIONS
BASELINE STUDIES
BENTHOS
BIBLIOGRAPHIES
BIOACCUMULATION
BIOASSAYS
BIOCONCENTRATION
BIOTURBATION
CHANNEL FLOW
CHEMICAL SPECIATION
DOMESTIC WASTES
ENVIRONMENTAL CHARTS
EUTROPHICATION
FLUVIAL DEPOSITS
FLUVIAL TRANSPORT
GEOLOGICAL SURVEYS
GROUNDWATER POLLUTION
INCINERATION
INDUSTRIAL WASTES
INTERNATIONAL AGREEMENTS
LAKE CURRENTS
LIMNOLOGICAL SURVEYS
LITERATURE REVIEWS
MASS BALANCE APPROACH
MATHEMATICAL MODELS
NON-POINT SOURCES
NUCLEAR POWER PLANTS
PEAT
PHOTOCHEMICAL REACTIONS
POINT SOURCES
POLITICAL ASPECTS
PORE WATER
RIVER PLUMES
SEASONAL VARIATIONS
SEDIMENT ANALYSIS
SEDIMENT DISTRIBUTION
SEDIMENT TRANSPORT
SEDIMENT-WATER INTERFACE
SEDIMENTATION
SEWAGE TREATMENT PLANTS
SORPTION
SURFACE FILMS
SUSPENDED PARTICULATE MATTER
TEMPERATURE CHARTS
TEMPORAL DISTRIBUTION
TEMPORAL VARIATIONS
WASTE DISPOSAL SITES
WATER COLUMN
WATER TRANSPARENCY
WATER TREATMENT PLANTS

Journal Title Abbreviations

Adv Chem Ser — Advances in Chemistry Series
Alternatives
Am Birds — American Birds
Am Fur Breeder — American Fur Breeder
Am Midland Nat — American Midland Naturalist
Ambio — Journal of the Human Environment, Research and Management
Anal Chem — Analytical Chemistry
Ann NY Acad Sci — Annals. New York Academy of Sciences
Appl Organometal Chem — Applied Organometallic Chemistry
Aquat Toxicol — Aquatic Toxicology
Arch Environ Contam Toxicol — Archives of Environmental Contamination and Toxicology
Ardea
Atmos Environ — Atmospheric Environment
Audubon
Auk — The Auk
Biol Conserv — Biological Conservation
Bird-Band — Bird-Banding
Bull Environ Contam Toxicol — Bulletin of Environmental Contamination and Toxicology
Can Entomol — Canadian Entomologist
Can Field-Nat — Canadian Field-Naturalist
Can J Comp Med — Canadian Journal of Comparitive Medicine
Can J Earth Sci — Canadian Journal of Earth Sciences
Can J Fish Aquat Sci — Canadian Journal of Fish and Aquatic Science
Can J Zool — Canadian Journal of Zoology
Can Mineral — Canadian Mineralogist
Can Special Pub Fish Aquat Sci — Canadian Special Publication of Fisheries and Aquatic Sciences
Can Vet J — Canadian Veterinarian Journal
Can Water Res J — Canadian Water Resources Journal
Cancer Res — Cancer Research
Chem Geol — Chemical Geology
Chemosphere
Coastal Oceanogr Climatol News
Colonial Waterbirds
Comp Biochem Physiol — Comparitive Biochemistry and Physiology
Condor
CRC Crit Rev Toxicol — CRC Critical Reviews in Toxicology
Environ Conserv — Environmental Conservation

Environ Geol Water Sci — Environmental Geology and Water Science
Environ Health Perspec — Environmental Health Perspectives
Environ Int — Environment International
Environ Mgmt — Environmental Management
Environ Monit Assess — Environmental Monitoring and Assessment
Environ Poll — Environmental Pollution
Environ Res — Environmental Research
Environ Sci Tech — Environmental Science and Technology
Environ Toxicol Chem — Envionmental Toxicology and Chemistry
Freshw Biol — Freshwater Biology
Freshw Invert Biol — Freshwater Invertebrate Biology
Geochim Cosmochim Acta — Geochimica et Cosmochimica Acta
Geosci Can — Geoscience Canada
Greenpeace
Hazard Waste Hazard Matr — Hazardous Waste and Hazardous Materials
Heavy Metals Environ — Heavy Metals in the Environment
Herpetol — Herpetologica
Hydrobiol — Hydrobiologia
Int J Environ Anal Chem — Internation Journal of Environmental Analytical Chemistry
Int J Environ Studies — International Journal of Environmental Studies
J Agric Food Chem — Journal of Agricultural and Food Chemistry
J Appl Ecol — Journal of Applied Ecology
J Appl Toxicol — Journal of Applied Toxicology
J Assoc Off Anal Chem — Journal. Association of Official Analytical Chemists
J Comp Path — Journal of Comparative Pathology
J Cons Int Explor Mer — Jounal du Conseil. Conseil International pour l'Exploration de la Mer
J Environ Anal Qual
J Environ Eng Div ASCE — Journal of the Environmental Engineering Division, ASCE
J Environ Sci & Health — Journal of Environmental Science and Health
J Field Ornithol — Journal of Field Ornithology
J Fish Biol — Journal of Fish Biology
J Fish Dis — Journal of Fish Diseases
J Fish Res Board Can — Journal of Fisheries Research Board Canada
J Geophys Res — Journal of Geophysical Research
J Great Lakes Res — Journal of Great Lakes Research
J Phys Oceanogr — Journal of Physical Oceanography

J Radioanal & Nucl Chem — Journal of Radioanalytical and Nuclear Chemistry
J Reprod Fertil — Journal of Reproduction and Fertility
J Sed Petrol — Journal of Sedimentary Petrology
J Toxicol & Environ Health — Journal of Toxicology and Environmental Health
J Wildl Dis — Journal of Wildlife Diseases
J Wildl Mgmt — Journal of Wildlife Management
Jack-Pine Warbler
Mar Environ Res — Marine Environmental Research
Mar Poll Bull — Marine Pollution Bulletin
Nat Can — Nature Canada
Naturaliste Can — Naturaliste Canadien
Natl Geog — National Geographic
Nature
New York Fish & Game J — New York Fish and Game Journal
Northeastern Environ Sci — Northeastern Environmental Science
Oceanus
Ont Field Biol — Ontario Field Biologist
Pest Monit J — Pesticides Monitoring Journal
Res Ocean Eng — Research in Ocean Engineering
Residue Rev — Residue Reviews
Rev Environ Contam Toxicol — Reviews of Environmental Contamination and Toxicology
Sci Total Environ — Science of the Total Environment
Science
Sedimentology
Toxicol — Toxicology
Trans Am Fish Soc — Transactions of the American Fisheries Society
Verh Int Ver Theor Angew Limnol — Verhanklungen der Internationalen Vereinigung fuer Theoretische und Angewandte Limnologie
Water Air & Soil Poll — Water, Air, and Soil Pollution
Water Poll Control J — Water Pollution Control Journal
Water Poll Res Can — Water Pollution Research Journal of Canada
Water Res Bull — Water Resources Bulletin
Water Res. — Water Research
Water Sci & Technol — Water Science and Technology
Wilson Bull — Wilson Bulletin